OPTIMISING DURUM WHEAT YIELD AND QUALITY

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Optimising durum wheat yield and quality

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Durum wheat (*Triticum durum*) produced in New Zealand is often of inconsistent yield and quality, where quality is specific to its utilisation in the pasta industry. Quality parameters include protein content and falling number of grain and flour, and flour and pasta colour. In this study, colour of grain, flour and pasta was quantified using the CIELAB colour space. High quality durum grain and flour was defined as that with high (>11.5%) protein content, high (>250 s) falling number and high (>18) b* value. The main research objective was to determine if the two management options available to growers, namely nitrogen (N) management and cultivar selection, could be used to produce high yielding crops with the desired quality characteristics including acceptable flour and pasta yellowness.

To do this the effects of different N fertiliser treatments on the yield and quality of 'CRDW17' and 'Waitohi' durum wheat were examined. Grain was produced from field experiments established at Darfield, Lincoln and Wakanui with a total of six N treatments applied early (tillering) and late (flag leaf emergence) during crop development.

At the dryland Darfield site, grain yield increased from 3.5 to 5.5 t/ha following 150 kg N/ha applied at tillering compared with increases from 4.5 to 7.0 t/ha at the irrigated Lincoln site after 175 kg N/ha. At Wakanui, early N did not increase yield due to 236 kg N/ha of available soil N at sowing.

Grain and flour protein percent were increased by both early and late N fertiliser. At all sites, crops which received early N achieved the industry standard of 11.5% for grain protein content. 'Waitohi' consistently had a protein content about 1% higher than 'CRDW17' across all N treatments, and the mean falling number value for 'Waitohi' was 20 to 90 s higher than for 'CRDW17'.

Grain b* value, or yellowness, was decreased by at least 1 unit when only early N was applied, and 'Waitohi' had a higher mean b* value than 'CRDW17' at all sites. In contrast, flour b* values for 'CRDW17' were increased by at least 1 unit at the three sites by early N application, leading to a negative correlation between grain and flour b* values. 'CRDW17' had a mean flour b* value at least one unit higher than 'Waitohi' at all sites and mean pasta b* values were higher for 'CRDW17' (27) than 'Waitohi' (24) at Darfield. The flour b* values were positively correlated with carotenoid concentration.

Optimal yield and required protein content can be consistently achieved by applying an appropriate amount of N fertiliser early in crop growth. In addition, early N application was not detrimental to flour and pasta b* values, and may increase yellowness. A definite method of increasing flour and pasta yellowness is to grow crops of 'CRDW17' rather than 'Waitohi'. However, industry should also consider

the other poorer attributes of 'CRDW17' for improvement through plant breeding. A compromise between colour and other quality attributes such as grain soundness, grain protein content and flour rheological properties all of which were superior for 'Waitohi', may be necessary to compensate growers for using 'CRDW17'.

ADDITIONAL KEYWORDS: Chroma; CIELAB colour space; falling number; flour; grain; hue; pasta; protein; rheological testing; *Triticum durum*.

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CHAPTER 1

Introduction

World wheat production is about 540 million tonnes annually with 90% of this consumed, in various forms, by humans. This means that wheat supplies about 20% of the total plant-derived edible dry matter for humans (Evans 1993). The superiority, and hence usefulness, of wheat among cereals results from the unique chemical and physical properties of the grain proteins it contains. When ground wheat grain (flour) is mixed with water, the wheat storage proteins bind to form a coherent mass of gluten (Stone and Savin 1999). Gluten gives the dough unique properties, such as the ability to expand to accommodate gas and stretch to bursting point, both aspects being essential in the production of wheat-based products.

About 90% of all the wheat produced in the world is 'common' hexaploid wheat (*Triticum avestivum*). This species encompasses hundreds of cultivars with a wide range of environmental adaptations and quality characteristics (Matsuo 1994). In the other 10% of production, *T. durum* is the most important type of wheat (International Wheat Council 1982). In 1994, the world production of durum wheat was 31 million tonnes, which was approximately 6% of total wheat production. The top five durum wheat producing countries in 1998 were Canada (4.8 million tonnes), Italy (4.0 million tonnes), Turkey (4.0 million tonnes), USA (2.6 million tonnes) and Kazakhstan (2.2 million tonnes) (Clarke *et al.* 1998).

The two main groups of consumers of durum wheat are in Europe and America, where 98% of it is used to make pasta products. In contrast, in the Middle East and North Africa other products are derived from durum. These include baladi, khobz, tannour, saaj and bulgur which all have similar quality parameters to those of pasta (Matsuo 1994). In these countries local bread-making accounts for about half of the durum consumption (Bozzini *et al.* 1988). In New Zealand, durum wheat is grown exclusively for extrusion to make pasta. This is a boutique industry with about 9000 tonnes of durum grain produced annually (Moyle pers. comm.).

Traditionally, durum wheat has been grown in semi-arid zones around the world. In the hot, dry environments crops usually produce low yields with high protein content. However, as with all wheat, the availability of nitrogen (N) from the soil and applied as fertiliser is an important factor to ensure optimal growth and quality (Grindlay 1997). The availability of N influences the yield potential of crops. Early in crop growth, N is required to ensure tiller production and survival, and it is also an important determinant of the number of grains per ear (Langer 1979). Later in growth, the availability of N during grain-filling strongly influences grain protein content, which dictates the potential end-uses of the wheat.

Grain produced in New Zealand often has inconsistent yield and quality, where quality is specific to a particular end-use. For durum wheat, important quality parameters include protein content, falling number (a low number indicates premature seed germination which reduces quality), water absorption and colour. One characteristic of durum wheat that readily distinguishes it from almost all cultivars of bread wheat is the high level of carotenoid pigments. The endosperm of durum wheat contains about twice the concentration of yellow carotenoid pigments present in bread wheat (Irvine 1971). The high carotenoid content confers an enhanced yellow/golden colour to the pasta made from it, and this is considered to be a desirable quality parameter by consumers (Moyle pers. comm.).

A key challenge facing the pasta industry is to produce high yielding durum crops with quality attributes that achieve the standards determined by industry, particularly high protein content and enhanced yellow colour. For bread wheat, N fertiliser applied to crops can increase grain yield (Stephen *et al.* 1985) and protein content (Scott *et al.* 1992) in N deficient soils. It is anticipated that agronomic N management will also increase the yield and protein content of durum wheat. In addition, it is proposed that it may be feasible to use N fertiliser treatments to increase the yellow appearance of pasta. Hence, the main research objectives of this thesis were to establish if agronomic N management could also be used to produce high yielding crops of durum grain with a protein content above 11.5%. In addition, to determine if N management could be used to increase flour and pasta yellowness. It was predicted that by generating a range of grain yield and protein contents that a range of grain, flour and pasta colours may also be generated. It was important to see if different cultivars responded to N treatment in the same way. The goals were to provide management guidelines to ensure profitability for growers, and produce grain and flour that are suitable for extrusion to acceptable pasta products for consumers.

To achieve the research objectives, a study was established with the experimental objective of investigating the effects of different N fertiliser treatments on the yield and quality of two cultivars of durum wheat, 'CRDW17' and 'Waitohi'. Thus, the experimental programme described in this thesis aimed to generate a range of grain yields and protein contents by sowing 'CRDW17' and 'Waitohi' at three sites in Canterbury (Darfield, Lincoln and Wakanui). Each site had different initial soil fertility and yield potential status. Different rates and timings of N fertiliser application were used to generate additional variation in yield and quality. Quality evaluation included standard testing used in industry for grain, flour and pasta quality attributes. Analysis aimed to establish the relationships between N availability, crop growth and quality of the resulting grain, flour and pasta.

Chapter 2 reviews the literature on yield and yield components, important durum quality parameters and the factors which influence these parameters. Chapter 3 deseribes the materials and methods used in the field experiments and the subsequent quality testing. Results for yield and N use, grain, flour and pasta quality are reported in Chapter 4. These results are discussed in Chapter 5 which also includes conclusions. This is followed by a general discussion, conclusions and recommendations for future research, in Chapter 6.

CHAPTER 2
Review of the literature

2.1 Introduction

Durum wheat produced in New Zealand is used solely for pasta making. The annual production of about 9000 t of durum wheat often has inconsistent yield and quality. In particular, New Zealand pasta colour is paler than other overseas products. High protein content and enhanced yellow appearance of the milled flour are the main quality attributes that are important to the pasta industry. Other quality parameters that also determine the quality of durum wheat include α-amylase content, water absorption, dough development time and dough stability time.

This literature review describes the importance of defining and assessing wheat quality in terms of attributes that make it suitable for particular end-uses. The important influence of N on the growth, yield and quality of wheat is highlighted. The components of the overall yield of the crop are examined, and the effects N has on them are discussed. Current procedures used to determine grain, flour and pasta quality are outlined and the constituents in the grain that affect the quality parameters are identified. The importance of the colour of pasta is discussed and the various methods used to measure it are outlined. The biochemical and physical factors influencing pasta colour are also highlighted. This is followed by a description of protein and carbohydrate accumulation in the grain and how these are affected by N availability. Finally, crop management procedures used to achieve maximum grain yield and quality are described. Where information for durum wheat is not present in the literature, examples from work carried out on bread wheat are reported.

2.2 Nitrogen availability

The optimum growth of wheat, as of any cereal, depends on adequate mineral nutrition. Arguably the most important nutrient is N. No other nutrient is needed in larger quantities in most environments, and no other is in such limited supply (Grindlay 1997). New Zealand soils commonly contain 0.1-0.3% N within the top 15 cm depth (Cameron 1992). Soil N availability management is a method used by New Zealand growers to manipulate yield and quality of durum wheat.

Soil N is present in three major forms; 1) organic compounds associated with plant material, soil organisms and soil humus, 2) ammonium ions (NH_4^+) held by clay minerals, and 3) plant-available mineral N (ammonium (NH_4^+), nitrate (NO_3^-) and nitrite (NO_2^-) in the soil solution (Cameron 1992). The lack of long-term storage of plant-available N and its susceptibility to being lost because of its high mobility, means that it is the element most likely to be deficient in wheat (Scott *et al.* (1992); Grindlay (1997)). The gains, losses and transformations of N in the soil can be represented in the form of a cycle (Figure 2.1).

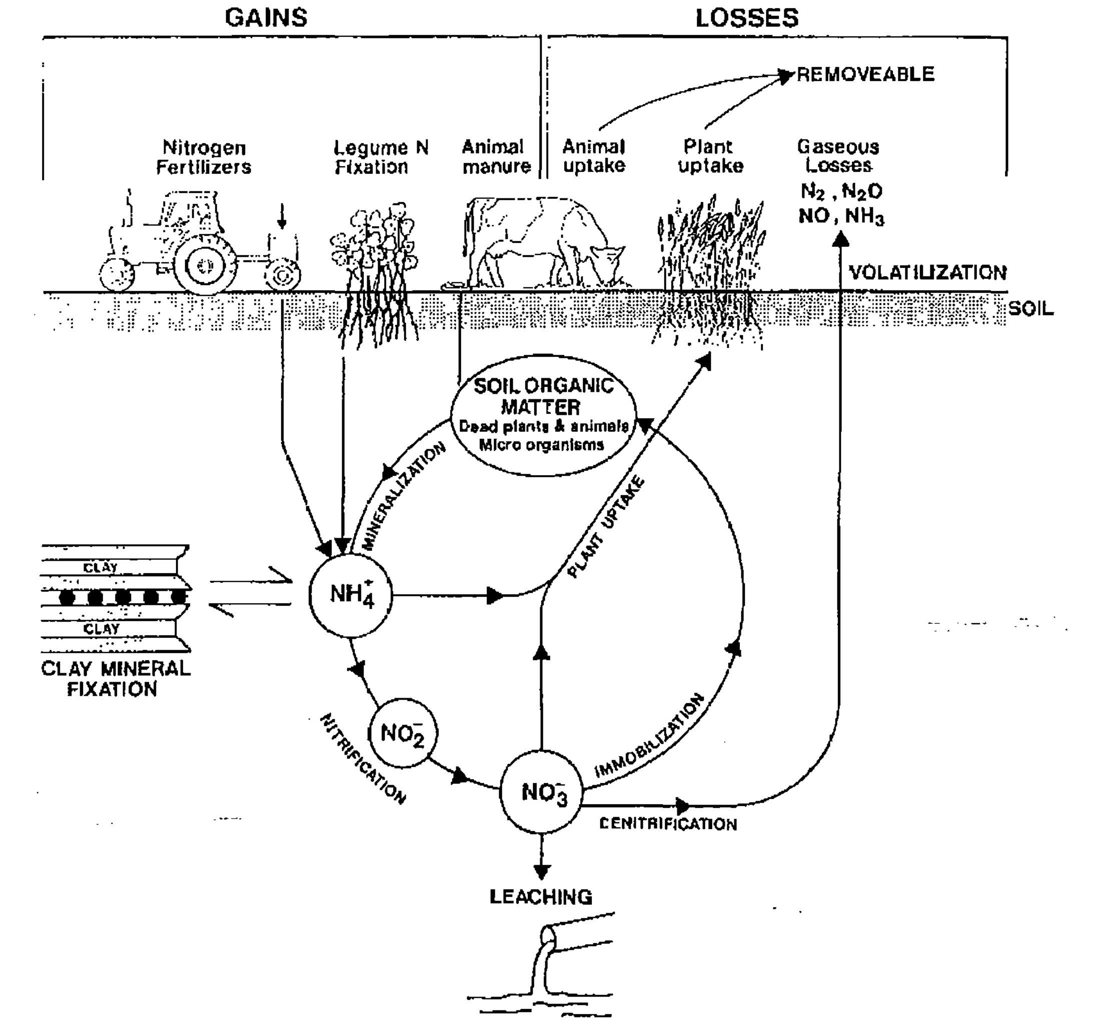

Figure 2.1 The soil nitrogen cycle. A summary of the inputs and losses of N in soil and the reactions and processes that N can undergo in an agricultural system.

Source: McLaren and Cameron (1996).

N can be gained by the soil via N fixation processes, atmospheric input, fertilisers and animal and plant returns (Figure 2.1). Gaseous losses of N occur via volatilisation of ammonia and denitrification of nitrate ions to dinitrogen gas (McLaren and Cameron 1996). Nitrate ions in the soil solution can be removed readily from the soil by leaching or plant uptake. However, the majority of N in soil is in organic forms which are unavailable to plants. Mineralisation is the continual turnover of organic N to mineral N, which is necessary to ensure N availability to plants. Aspects of soil N forms, amounts and availability have been extensively reviewed by McLaren and Cameron (1996).

All N in grain comes from the soil, and it reaches the grain in two ways. Most grain N is taken up by the crop prior to anthesis and stored in the upper leaves and stem, and then is remobilised to the grain after flowering (Martin *et al.* 1989). Remobilisation can occur because the leaf N concentration is dynamic due to the solubility of N compounds (Grindlay 1997). For example, remobilisation of N from the vegetative tissue during reproductive growth of barley was reported by Fergusson (1999) (Table 2.1). The rest of the grain N is taken up from the soil after flowering and translocated directly to the grain (van Keulen and Seligman 1987).

Table 2.1 Change in nitrogen (kg/ha) between anthesis and final harvest, total N in grain and screenings, and the amount of N relocated to grains during grain filling in barley grown with different N fertiliser treatments.

Treatment (kg N/ha)	Increase from anthesis to final harvest	Grain + screenings		Change of nitrogen (exclusive of grain +screenings)	
0	42	63	d	-21	b
50	48	94	c	-46	ab
100	43	106	bc	-63	ab
150	39	126	ab	-87	a
150/50*	56	125	ab	-69	a
150/100*	76	139	a	-63	ab
SEM	11.6 (ns)	4.7		10.6	

Note * = treatments where a second application of N fertiliser was applied 56 DAS.

Source: Fergusson (1999)

Fergusson (1999) found that relocation of N from biomass to grain and screenings occurred in all treatments. In the 150 kg N/ha treatment, 87 kg N/ha was relocated to the grain + screenings between anthesis and final harvest. In all of the other treatments, a smaller amount than this was relocated, with only 21 kg N/ha relocated in the nil N treatment. More translocation occurred when more N fertiliser was applied. Crops with a larger N pool are less likely to take up N after anthesis, and there was an increased likelihood of sustained relocation to the grain (Fergusson 1999).

A measure of the efficiency of N relocation in the plant is the N harvest index (NHI). NHI is the proportion of total N in the above ground plant material that is in the grain (Blacklow and Incoll 1981). NHI is usually variable, and changes depending on the proportion of N relocated from pre-anthesis reserves and the contribution from late N uptake during grain-filling (Blacklow and Incoll 1981). For example, Fergusson (1999) found that in barley the NHI was reduced when split applications of N were used and that the low N treatments relocated more N from the biomass to the grain. Assuming other nutrients and water are unlimiting, the availability of N to the crop dictates its potential yield and quality.

2.3 Yield and yield components

There are many ways to describe the structure of yield. The simplest is to say that the aim is to produce the optimum number of grains of adequate size per unit area the optimum depending on the grain yield potential of the site. The components of yield can then be expressed as:

Equation 1:

Grain yield/m^2 = ears/m^2 x spikelets/ear x kernels/spikelet x mean kernel weight.

Source: Scott *et al.* (1992).

One or more of these components is being determined continuously from the day a crop is sown (Power and Alessi 1978). High grain yield is achieved by managing a crop to give a high target grain population and to avoid stresses which can shorten the duration of the crop canopy, such as drought, lodging, leaf diseases and N deficiency (Hay and Walker 1989). N availability influences grain yield in two main ways. Firstly, N increases leaf area of the crop and enables greater interception of photosynthetically active radiation (PAR) over the growing season (Hay and Walker 1989). Secondly, N improves the efficiency of conversion of intercepted PAR into biomass. When N availability decreases, the biomass produced per MJ PAR may decline (Hay and Walker 1989).

A comparison of wheat cultivars bred in Britain from 1908 until 1978 showed that the greater yields of modern cultivars could not be attributed primarily to any single yield component. High yields clearly resulted from various combinations of yield components (Austin *et al.* 1980). Variation in grain yield can commonly be attributed to variation in grain population/m^2, this being the product of the first three yield components namely ears/m^2, spikelets/ear and kernels/spikelet (Ellen and Spiertz 1978). Jamieson and Wilson (1992) used grains/m^2 as a primary component of yield in their 'Sirius' crop model rather than ears/m^2, due to it being a combination of the first three yield components and, therefore, a more stable component.

It is well known that N fertiliser applied early in the development of a crop (prior to stem elongation) stimulates tiller production (Langer 1965). Early N application increases grain yield by increasing tiller production and decreasing tiller mortality, leading to an increase in the number of ears which produce grain (Stephen *et al.* 1985). This response has been attributed to N application increasing the size of the tillers, which enhances their ability to survive and produce ears (Thorne and Wood 1988), and hence increase yield (Table 2.2). Grain yield was increased by early N application, through increasing the ear population and the number of grains/ear. Mean grain weight was similar in all treatments. Langer and Liew (1973) found that by increasing the N supply before the terminal spikelet was initiated, the number of spikelets present increased.

Table 2.2 Grain yield and yield component values for wheat crops grown with different rates of N applied early (tillering) or late (booting).

Nitrogen (kg/ha) Early:Late	Grain yield (t/ha)	Ears/m^2	Grains/ear	Grains/m^2	TGW (g)
0 : 0	5.17	495	29.6	14652	44.9
50 : 0	5.90	531	32.4	17204	44.6
50 : 50	6.41	544	32.8	17843	46.6
100 : 0	6.50	550	33.8	18590	45.4
100 : 50	6.85	561	33.6	18849	46.4
LSD (5%)	0.20	30	1.3	-	0.70

Note: * =grains/m^2 were derived from the measured ears/m^2 and grains/ear yield components.

Source: Martin *et al.* (1992).

Grain weight is a relatively stable characteristic of a given cultivar (Gallagher *et al.* 1975). The increase in wheat grain weight appears to be under genetic control (Hunt *et al.* 1991) with endosperm cell number having a positive effect on kernel growth rate (Brocklehurst 1977). It is known that endosperm cell number is closely related to final grain weight and this may regulate the demand for assimilate (Brocklehurst 1977). Little is known about genetic variation in this trait or whether it can be manipulated (Slafer *et al.* 1999).

In Table 2.2 the N applied at tillering had little effect on grain weight, although N applied at booting increased grain weight by an average of 1.5 mg (Martin *et al.* 1992). However, there is often an inverse relationship between grain weight and grain N content (Scott *et al.* 1992). In most cases, N applied at tillering slightly decreases kernel weight (Drewitt and

Dyson 1987). This is probably due to the increased tiller survival bought about by early N application and this may reduce thousand grain weight (TGW). Secondary or tertiary ears produced after early applications of N are often smaller than the primary ears and, hence, they produce fewer, smaller grains leading to an overall decrease in TGW (Power and Alessi 1978).

2.4 Wheat quality

Despite the importance of yield in relation to overall profitability to the grower, in the present study the primary focus was on quality and its importance in determining the end-use of the wheat. Since deregulation of the wheat industry, grain produced in New Zealand must meet strict quality standards to compete with imported wheat (Martin 1987). The emphasis for growers is to produce high yielding crops of high quality to ensure optimum profit.

For many years, cereal chemists have been trying to define, understand and measure wheat quality (Tipples *et al.* 1994). Quality is determined by the size, shape, structure and composition of the mature grain. Therefore, it is a highly complex character resulting from the interaction of many biochemical processes and a large number of genes (Stone and Savin 1999). Certain attributes determine the quality and suitable end-use of a line of wheat. Emphasis is placed on protein content, gluten strength and grain soundness. To some degree these parameters can be manipulated by agronomic treatments, but the genetic make-up of the crop and the environment are the predominant determinants.

2.5 Wheat type

Wheat type is determined by hardness, gluten strength and protein concentration. In New Zealand, four major types of wheat are grown; biscuit, bread (or milling), feed and durum wheat. Each is grown for a specific use depending on the attributes of the wheat and flour. Conventionally, wheat with low protein content (8-9%) and weak gluten strength is used for the biscuit making industry. Biscuit cultivars are often referred to as 'soft' wheat due to their genetic association with low grain hardness. Bread making requires wheat with medium to high protein content (11.3-12.5%) and sufficient gluten strength to allow the bread to rise. Most bread cultivars are hard wheats. Cultivars bred specifically for stock feed are often much higher yielding than milling ones but the required protein content is only 10% and gluten strength is not important. Durum wheat typically has a protein content the same as, or greater than, bread wheat and medium to strong gluten strength (Dexter and Matsuo 1980). Durum wheat is used for pasta making predominantly due to its amber-golden flour colour which is desirable for pasta production. It is the hardest of all the wheat types. A major source of variation for grain hardness has been assigned to the short arm of chromosome 5D (Mattern *et al.* 1973). Consequently, durum wheats which lack the D genome are very hard, while hexaploids may be soft or hard depending on the allelic state of the genome (Morris and Rose 1996). A wheat grain contains many different proteins with different functional and chemical properties. The genetic make-up of a cultivar determines which proteins are likely to be produced in abundance compared with others.

2.6 Types of protein in wheat

Different fractions of wheat protein have been defined based on their solubility. The fractions have been classified by sequential extraction of the proteins in increasing strength solutions (Figure 2.2).

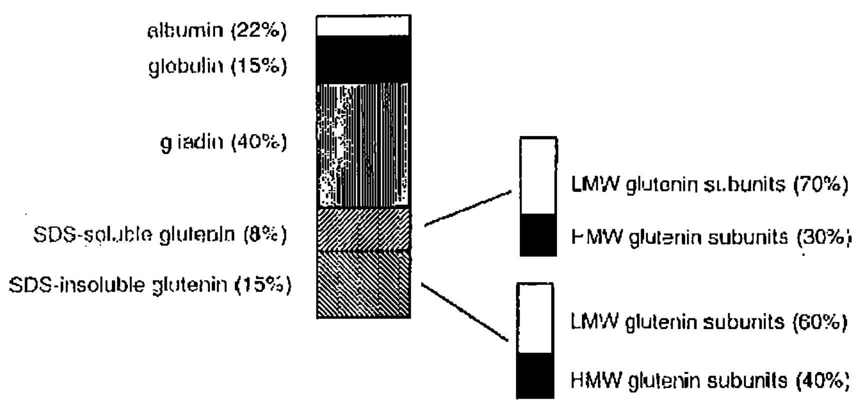

Figure 2.2 Protein composition of a typical wheat grain

Source: Stone and Savin (1999)

The first class contains the albumins, which are soluble in water. The second is globulins, which are insoluble in water but dissolve in dilute salt solution and the third is gliadins which are insoluble in water and saline but soluble in 70 percent aqueous ethanol. The final class is glutenins which are not soluble in any of the above solvents (Osborne 1907). Fractionation on this basis, followed by Kjeldahl N analysis of each fraction, enabled early workers to determine grain protein composition accurately and relate it to flour and dough properties.

Albumin and globulin are metabolic proteins and typically make up 20-30% of the total grain protein (Jennings and Morton 1963), although this can vary with genotype and N nutrition. Despite the abundance of these in the grain, albumin and globulin have relatively minimal impact on dough strength and end-use quality. They play only a minor role in the protein interactions that are required for the formation of gluten because they are not chemically suited for protein-protein interactions (Schofield 1994) and hence do not instil any rheological properties to the dough. However, they are essential for the growth and development of the wheat seedling (Dell'Aquila *et al.* 1983) which relies on energy and nutrients made available by their hydrolytic and proteolytic capacity.

Storage proteins comprise the remaining 70-80% of the grain protein (Figure 2.2). The principal role of storage proteins is to provide energy for the germination and growth of wheat seedlings. However, these proteins are also primarily responsible for the physical properties of the dough, and consequently, many aspects of grain quality (Stone and Savin 1999). The storage, or 'gluten', proteins fall into two major classes: the gliadins and the glutenins. Gliadins are the smaller of the two and are generally non-aggregating, and hence do not join together to form large polymer chains. They are monomeric so do not contribute to the strength of the gluten but rather to its extensibility due to their ability to act as a 'lubricant' within the dough. Glutenins are less soluble and bigger than gliadins. Glutenins have the ability to aggregate through the formation of disulphide bonds between cysteine residues in glutenin molecules (Tipples *et al.* 1994) to form membrane-like gluten films in the dough which instil strength into the dough. These act to trap carbon dioxide (CO_2) and other gases emitted during the baking process and allow bread to rise. Gluten is found in each type of wheat, but the strength of gluten depends on the cultivar, soil fertility and environmental conditions.

The glutenin proteins can be divided further into subclasses on the basis of their solubility in dilute detergent, sodium dodecyl sulphate (SDS) (Figure 2.2) (Gupta *et al.* 1993). The SDS-soluble glutenins tend to be smaller and contribute less to the dough strength than those which are SDS-insoluble. This appears to be related to the size of the protein subunits of each molecule (Gupta *et al.* 1993). In general, the greater the proportion of high molecular weight (HMW) glutenin subunits in a molecule the greater is its ability to form a macromolecule, and this contributes to increased dough strength. In contrast, the SDS-soluble glutenin proteins contain a smaller proportion of HMW subunits, reducing their contribution to dough strength (Gupta *et al.*1993). However, a combination of both low molecular weight (LMW) and HMW glutenin subunits is required for maximum dough strength (Gupta *et al.* 1994).

2.7 Effect of protein content on pasta quality

Generally durum wheat has an average protein content the same or higher than that of bread wheat, but it may vary from 9-18% (Feillet 1988). Boyacioglu and D'Appolonia (1994) reported that durum flour had higher wet and dry gluten contents than did the bread wheat flours. In the bread baking industry, flour with high protein content has a high loaf volume potential, high water absorption and produces loaves with good keeping quality (Tipples *et al.* 1994). Similarly in the pasta industry, high protein content and 'strong' gluten are required to process semolina into a suitable final product because the protein content is responsible for the cooking quality of pasta products.

Wheat protein content seems to account for 30 to 40% of the variability in pasta cooking quality (Feillet 1988). Matsuo and Irvine (1970) reported that wheat with 13% or higher protein content made a satisfactory pasta, whereas a protein content lower than 11% gave a pasta with poor cooking quality. Walsh and Gilles (1971) concluded that durum wheat cultivars with a high content of glutenins (and albumins) tended to show good cooking quality. Dexter and Matsuo (1980) confirmed that a high glutenin:gliadin ratio (1.15:1.00) was related to superior cooking quality because high gliadin content seemed to be related to low cooked pasta firmness. However, there seems to be a linkage between the presence of certain gliadins and superior pasta cooking quality. Results suggest that durum wheat cultivars with 45-γ gliadin fraction have higher intrinsic cooking quality, whereas those with 42-γ gliadin fraction have poorer cooking quality (Feillet 1988). Analysis of the polyacrylamide gel electrophoresis (PAGE) gliadin patterns and gluten visoelasticity of 75 durum wheat cultivars showed that the presence of the 45-γ component was linked to strong gluten and hence high quality pasta, whereas 42-γ was linked to weak gluten strength (Damidaux *et al.* 1978).

2.8 Tests for assessing the types of protein in wheat

Over time various methods have been developed to isolate and quantify wheat proteins. The differences in composition of soluble proteins from bread and durum wheats were recognised first by Pence *et al.* (1954) using paper electrophoresis. Their findings were confirmed by Feillet and Bourdet (1964) who ran starch gel electrophoresis to compare durum and bread wheats. Using PAGE Silano *et al.* (1968) showed that certain globulin and albumin components occurred only in bread wheat. Wrigley *et al.* (1982) reported that identification of durum wheat cultivars was also possible using acid-PAGE (A-PAGE) electrophoresis of gliadin due to proteins being direct products of gene transcription and translation.

More recently, high performance liquid chromatography (HPLC) has been utilised to separate and quantify proteins. HPLC allows the full compliment of proteins to be analysed simultaneously. An improved understanding of the mechanics of protein accumulation may expedite attempts to manipulate the nutritional value and end-use quality of wheat. Through agronomic treatments growers have learned how to use N fertiliser to increase grain protein content and hence improve wheat quality. However, despite the emphasis cereal chemists have placed on isolating different types of protein fractions, payment for wheat growers is based on total protein content with no discrimination among types. Despite the importance of protein content when assessing wheat quality, the majority of the grain is composed of carbohydrate.

2.9 Carbohydrate

A wheat grain is dominated by carbohydrate, which constitutes approximately 70% of the grain mass. Almost all of the carbohydrate is present as starch, with the remainder (less than 3%) comprising sucrose, glucose, fructose and other less abundant sugars (Boyacioglu and D'Appolonia 1994). This composition may be drastically altered if even a small amount of sprouting occurs. Although these sugars are not present in great quantities, they are important during proving and baking of bread, as they contribute to the sugar required by the yeast for the initial production of CO_2 (Sutton pers. comm.).

2.10 Starch

Starch occurs as small granules which are packed densely in the endosperm of the grain and serve as the principal supply of energy for the germinating seed and early growth of the seedling. Wheat starch is made up of two main fractions, amylose and amylopectin, which make up about 25 and 27% of the total starch mass respectively (Leloup *et al.* 1991). In the bread and pasta making processes starch plays a number of important roles. It reinforces the gluten network by providing a semi-solid structure to which gluten can adhere. Since starch is present as discrete granules, it can move around in the dough to fill up spaces that are created as the loaf changes shape during baking (McGee 1991). Starch also has an important role in determining pasta and bread quality, yet it is seldom considered an important quality parameter. Often this is due to the fact that starch composition is much more stable than protein across genotypes and environments.

In their original state starch granules are insoluble in water, although the damage which occurs during milling often makes them soluble. This property gives starch its important role in water absorption by flour. A certain amount of this damage is desirable as it provides a substrate for α-amylase to produce sugars for fermentation (Sutton pers. comm.) and increases the water absorption of the flour. However, if the damage is too severe the flour forms a 'sticky' dough because the 'scaffolding' of the dough is damaged. Starch damage is usually higher for hard bread wheat (7-8%) than for soft biscuit wheat (3-5%). More energy is required to grind the hard wheat into flour, and so more starch is damaged. About 11.5% starch damage occurs in hard durum wheat during milling (Moyle pers.

comm.). A high water absorption value results from a high number of damaged starch granules, as they absorb more water than intact granules.

2.11 Water absorption

Water absorption is an important quality factor for pasta making because it determines the amount of pasta that can be produced from a given weight of flour. Water absorption depends on two factors: the damaged starch level of the flour and the flour protein content. A higher amount of starch damage in durum wheat results in higher water absorption values (70-74%) compared with softer bread wheat (63-66%) (Moyle pers. comm). Durum wheat also has higher water-binding capacity and a slower water absorption than other hard wheats. This accounts for the slower staling and consequently longer shelf life of bread made from durum flour (Luraschi 1955).

N fertiliser applications can be used when growing wheat to increase the protein content (Section 2.6) in the grain if the amount of N available to the plant exceeds the requirements from the vegetative part. This use of fertiliser has also been shown to increase water absorption. For example, Martin *et al.* (1992) showed that water absorption increased from 58.6 to 61.3% when a total of 150 kg N/ha was applied during crop growth (Table 2.3). The results also illustrate the positive relationship between protein content and water absorption as both increased with early and late N applications.

Table 2.3 Bread flour water absorption and protein content values from wheat crops with different N fertiliser applications early and late in crop development.

N applied (kg/ha) (Early : Late)	Water absorption (%)	Protein content (%)
0 : 0	58.6	9.4
50 : 0	59.4	10.0
50 : 50	61.8	11.5
100 : 0	60.3	11.0
100 : 50	61.3	12.1
LSD (5%)	1.5	0.3

Source: Martin *et al.* (1992)

A farinograph test is used to measure the water absorption of flour. The amount of water that needs to be added to a specific weight of flour to produce a dough with a certain maximum consistency is determined. The dough is mixed at a specified (standard) speed in the Brabender Farinograph (a torque measuring, recording dough mixer). This method is widely used in the bread and pasta making industries as the preliminary estimate of water absorption, because it is important to know the exact amount of water that needs to be added to make either bread or pasta of a specified consistency. Dough stability time and dough development time are also measured from a farinograph test.

2.12 Dough stability time

The stability time for dough is a measure of how tolerant its gluten is to over-mixing. This gives a good indication of the dough strength. Typically durum wheat has a large range of values for stability time, from about 5.0 to 9.0 minutes (Moyle pers. comm.).

2.13 Dough development time

Dough development time is a measure of the mixing time needed for the gluten to develop in the dough. This is used by bakers to indicate the work required to mix the dough to a particular consistency. The dough development time for durum wheat usually ranges from 2.5 minutes to 4.5 minutes (Moyle pers. comm.).

2.14 α-amylase content

Durum wheat is susceptible to sprouting prior to harvest in moist conditions. Soundness is an important quality factor that influences pasta making and baking quality. Sound wheat, with no sprout damage, contains low levels of α-amylase enzyme (Tipples *et al.* 1994). α-amylase is an endosplitting enzyme that hydrolyses the α-1,4-glycosidic bonds of starch molecules and derived polysaccharides in a more or less random fashion (Fabriani and Lintas 1988). This results in the starch molecules being liquidised into simple sugars. Grains within the ear may begin to sprout pre-harvest if the conditions are sufficiently moist or humid. A rain event when the grains are filling or reaching physiological maturity may be sufficient to trigger 'pre-harvest sprouting' or germination.

Germination is associated with a rapid increase in α-amylase activity as simple sugars are required by the developing embryo for energy. A severely sprouted kernel may be subject to several thousand times as much enzyme activity as a sound kernel (Fabriani and Lintas

1988). Sprout damage can cause severe baking and pasta making problems such as, sticky dough, lower water absorption and uneven hydration (Dexter *et al.* (1990); Matsuo *et al.* (1982)).

Visual sprout damage can be used to assess kernels that are sprouted. Moot and Every (1990) found that visible sprout damage was a poor indicator of sprout-damage-related baking problems. A much more reliable test is the falling number test. The falling number test is often used to predict the amount of starch degradation in the wheat kernel by measuring levels of α-amylase enzyme present. Moot and Every (1990) found that the falling number method of sprout damage assessment clearly distinguished wheat samples of sound baking properties from sprout-damaged samples.

Another method involves the determination of α-amylase activity in the flour. This was also found to be a reliable method in the determination of sprout-damaged samples (Moot and Every 1990). Visibly sprouted samples had a falling number test result of less than 200 seconds and α-amylase activity of greater than 0.4 units of enzyme /g flour. Boyacioglu and D'Appolonia (1994) found lower levels of α-amylase activity (higher falling number values) in durum flour compared with bread flour. A study conducted on Italian durum wheat flour by Boggini (1985) showed falling number values of between 264-526 seconds for durum flour compared with bread flour which usually has values between 250-400 seconds (Moyle pers. comm.).

In most cases, a small amount of sprout damage is not a problem and industry typically accepts durum with a falling number over 250 seconds. However, in some industry situations a relatively minor case of sticky crumb can still play havoc with bread slicing equipment, which severely interrupts the process chain.

2.15 Lipids

Lipids constitute approximately 2% of the mass of flour. These lipids are essential in bread making. If they are removed the dough will not rise during baking. There is evidence that lipids are involved in the binding of gliadin and glutenin within the gluten structure, and of the gluten to starch within the dough as a whole (Soulaka and Morrison 1985). A higher lipid content is found in durum wheat and durum semolina than in bread wheat and bread flour respectively, although the fatty acid compositions are similar. Typical values for total lipid content are 33 g/kg for whole durum grain and 18 g/kg for the semolina (Laignelet 1983). Lipids are important for the pasta industry as they represent the pigments present in the wheat. In particular, carotenoids are lipids that determine the colour of flour and pasta (Borrelli *et al.* 1999).

2.16 The importance of colour

The colour of pasta is the most important factor that consumers associate with quality (Clarke *et al.* 1998). Consumers believe that pasta with a golden appearance has higher quality than paler pasta. High yellow pigment content is desirable to ensure that the pasta has an intense amber colour (Clarke *et al.* 1998).

2.17 Wheat pigments

The colour of pasta is a result of the relative proportions of pigments in the wheat grain. Carotenoid pigments are responsible for the colour of durum wheat and flour. They are natural compounds that reduce the oxidative damage to biological membranes by scavenging peroxy-radicals (Borrelli *et al.* 1999). Durum wheats generally have higher carotenoid content than bread wheats. For example, durum and bread flour containing 3.7 and 2.8 mg/kg respectively (Lepage and Sims 1968).

Markley and Bailey (1935) showed that the predominant carotenoid pigments in the extracts of ground durum wheat grains are xanthophylls. Lepage and Sims (1968) confirmed this finding using chromatographic and spectrophotometric methods. The xanthophyll pigments in grain occur as unesterified or as mono- and diacyl esters and represent 90% of the total carotenoids. The main carotene isomer in wheat grain is β-carotene, but α-carotene has also occasionally been reported (Laignelet 1983).

2.18 Colour measurement

The colour of an object is determined by three factors: its illumination, reflection of light from it and the translation of a colour by the eye and brain of the observer or detector (Morgenstern 1992). Three main methods are used to measure colour; image analysis, colour grade and tristimulus colour measurement.

2.18.1 Image analysis

For colour determination using the image analysis method, images are usually taken with a television camera and stored in a digital memory. The image is analysed by computer, by measuring the red, green and blue component of each pixel separately.

2.18.2 Colour grade

A colour grade is commonly used in a mill laboratory to determine the 'whiteness' of a line of flour. Its use is based on the inverse relationship with bran content and the whiteness of flour. This is what makes the colour grade ideal for use on bread flour as it provides a measure of the whiteness of the final bread product. The Kent-Jones and Martin colour grade measures the fraction of reflected light from a flour and water paste using a green filter, which has maximum transmission in the region of 540 nm. This makes the measurement less sensitive to the yellow pigments in the flour. The colour of a sample is denoted one value, known as its colour grade. For this reason the colour grade value can not be related to human perception, since human perception is described by three parameters. Due to colour grade's lack of suitability for determining yellow colour along with its reduced sensitivity, it is usually avoided for durum samples and a tristimulus colour measurement is preferred.

2.18.3 Tristimulus colour measurement

Perception of colour is described fully by three parameters: hue, chroma and lightness. Therefore colour measurement can be represented in a three dimensional colour space. Hue is described by a word such as blue, red, yellow etc. Chroma (also known as saturation or purity) relates to the intensity or amount of colour and lightness which is related to the total amount of light that the eye receives (Gonnet 1995). The CIELAB colour space is closely correlated with human perception, and is the recommended colour space.

In CIELAB both illuminant and observer are standardised and, by measuring the light reflected from an object, its colour is expressed in three values L*, a* and b* (Figure 2.3). L* denotes its lightness on a scale from 0 (black) to 100 (pure white), a* is a value on the red-green scale (-60 to +60) and b* is a value on a yellow-blue scale (-60 to +60) (Morgenstern 1992). Since the yellow colour of pasta is an important quality parameter, the b* values are particularly important.

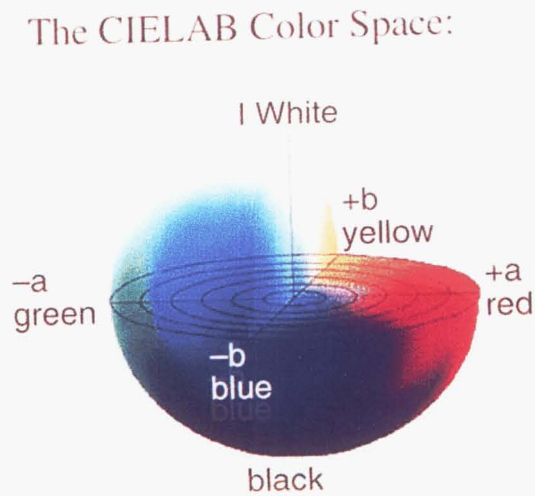

Figure 2.3 L*a*b colour space

Source: Adapted from Gonnet (1995)

The combination and transformation (Equation 2, 3) of a* and b* values allows the determination of a hue angle (Figure 2.4) and chroma for each sample (Figure 2.5).

<u>Equation 2:</u>

Hue angle = $\tan^{-1} b/a$

<u>Equation 3:</u>

Chroma = $(a^2 + b^2)^{1/2}$

Source: Little (1975).

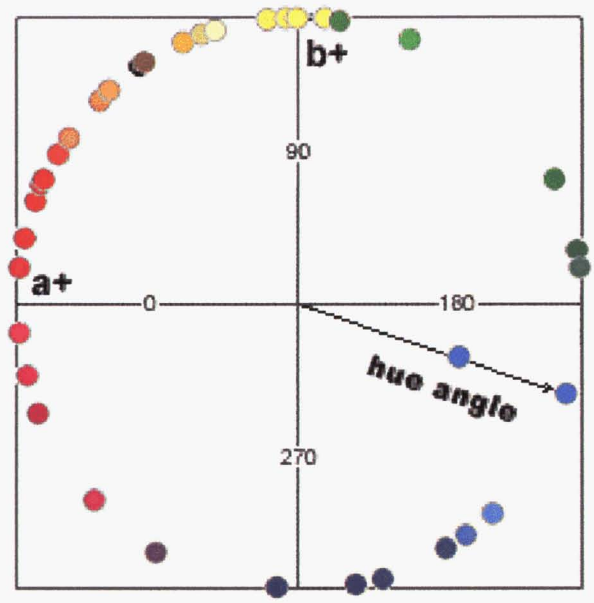

Figure 2.4 Relationship between a* and b* values and corresponding hue angle .

Source : Adapted from Gonnet (1995)

The combination of hue, lightness (L*) and chroma puts colour on a three dimensional axis (Figure 2.5). Equation 3 can be applied to measured parameters a* and b* to calculate chroma values.

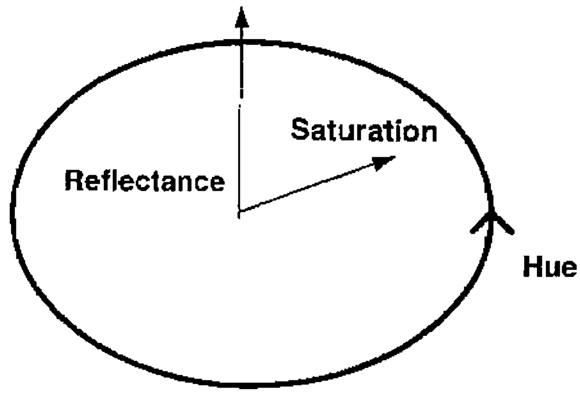

Figure 2.5 Relationship of the attributes of colour in three dimensional space

Source: Adapted from Gonnet (1995)

The CIELAB Minolta colour space was used by Johnson *et al.* (1997) to determine the preferred groat colour for the oat industry. The colour space was used in the present study due to its high correlation with human perception and its ease of use.

2.19 Biochemical and physical factors that affect durum colour

The inherent carotenoid pigment content of the grain is a cultivar characteristic (Irvine and Anderson 1953). Due to the carotenoid content being genetically determined, cultivar selection is proposed as a management tool to increase the desired yellowness of pasta in this study.

Pasta yellowness is also affected by various physical and biochemical factors. However, the effect of N fertiliser on the yellow colour and hence carotenoid content has not previously been reported. It is hypothesised in this study that through a combination of N fertiliser management and cultivar selection the yellow appearance of pasta will be enhanced.

Physical factors that influence the carotenoid content of grain or flour include growing conditions, disease infection, grain and flour storage conditions and milling extraction rate. Laignelet (1983) reported that heavy rain during ripening resulted in grain that was whiter in appearance and less vitreous. Furthermore, one of the most common fungal diseases that affects flour colour is black point caused by *Alternaria alternata* (Cromey and Mulholland 1988). In addition, Dexter *et al.* (1997) found that yellow semolina colour was affected adversely when the grain was contaminated with *Fusarium graminearum* because it made the semolina appear duller and redder.

Destruction of carotenoid pigments may begin during grain storage and then increase further during milling and after extrusion, when the cellular structure has been disrupted (Laignelet 1983). The carotenoid pigments are not distributed homogeneously in the wheat kernel (Borrelli *et al.* 1999). Embryo, bran and endosperm contain decreasing amounts of β-carotene (Quaglia 1988). During milling, depending on extraction rate, a variable amount of these pigments may be lost initially. In addition, pasta processing results in a large decrease in carotene content. Borrelli *et al.* (1999) calculated that a 7.9% loss of β-carotene resulted from milling compared with 16.3% lost during pasta making.

During pasta processing there is an oxidative degradation of pigments by the lipoxidase (LOX) enzyme in the pasta (Irvine and Winkler (1950); Irvine and Anderson (1953); Irvine (1959)). LOX catalyses the addition of molecular oxygen to fatty acids. The fatty acid radicals produced from this addition are responsible for the oxidative degradation of pigments such as β-carotene, xanthophylls and chlorophylls (Borrelli *et al.* 1999), resulting in an overall bleaching effect of durum products. The extent of carotenoid loss during pasta making is influenced by wheat cultivar and may range from 30 to 60% in some cases (Irvine and Anderson 1953). In addition, the drying process of pasta making is also known to affect the amount of pigment lost from the pasta. Matsuo *et al.* (1970) predicted that a further 20% of the pigments could be lost during drying.

Several methods to prevent the bleaching of the yellow colour during pasta manufacture have been investigated. The most effective method to date is the use of a vacuum, which removes the molecular oxygen necessary for the oxidative bleaching reaction and also prevents air bubble formation in the dough (Irvine 1971). The use of high temperatures (+55°C) for drying denatures the LOX enzyme and limits pigment degradation. However, high temperatures also promote the onset of browning in the pasta so this is not a possible solution to the problem (Laignelet 1983). A chemical approach to avoiding pigment loss is the use of chemical inhibitors of the oxidation reaction. A substance shown to inhibit carotenoid pigment degradation is sodium chloride, which has also been shown to limit pasta browning (Laignelet 1983).

2.20 Crop growth/management and wheat quality

Adoption of agronomic practices such as strategic N fertiliser application requires an understanding of the physiological processes and interactions that determine yield and quality of wheat. Strategic N fertiliser applications are a management tool used by growers to manipulate yield and quality of the harvested grain. Traditionally, wheat cultivars were bred and selected mainly for yield, as growers were not rewarded for producing grain above a certain minimum quality. Fertiliser management was aimed solely at increasing yield and this involved completing N applications before stem elongation, to ensure high grain set and hence yield, though this was often at the expense of low grain size and protein content (Martin *et al.* 1992). Following the deregulation of the wheat industry in the mid 1980's, New Zealand growers had to compete with imported wheat. This meant that they needed to meet strict quality standards and also maintain high yields to remain commercially viable. An efficient N fertiliser management program coupled with an understanding of the growth and development processes in a crop were required to achieve maximum yield and quality.

Grain growth and development was described by Jenner *et al.* (1991) as the product of two processes: kernel enlargement and grain filling (Figure 2.6).

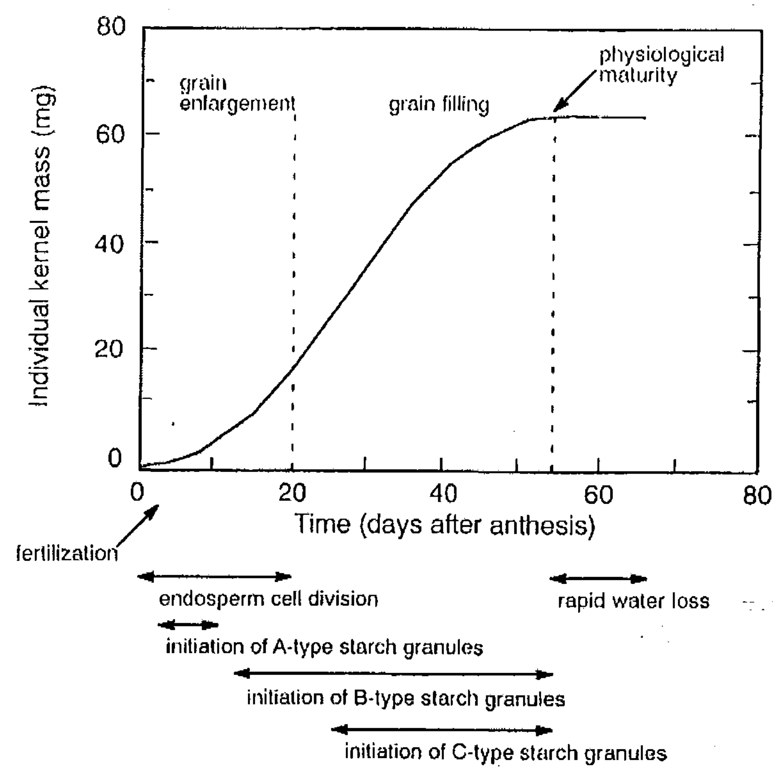

Figure 2.6 The growth of a wheat kernel, showing key events in starch accumulation

Source: Stone and Savin (1999).

Grain enlargement occurs first, as it is the process that builds the structures into which starch and other constituents of the endosperm will be added during grain filling. Grain enlargement commences after fertilisation and lasts for about 20 days (Jenner *et al.* 1991). However this duration depends on temperature, with about 650°Cd required to reach physiological maturity (Moot *et al.* 1996). Enlargement is the process where cell nuclei multiply via mitosis and then expand. At this point the endosperm can be characterised as a large bag filled with about 100,000 smaller bags, each containing a nucleus, a lot of water and the first traces of starch and protein. This marks the end of the lag phase and the start of grain filling. During grain fill both proteins and carbohydrates accumulate in the grain.

2.21 Protein accumulation

During grain growth, storage proteins are deposited in discrete membranous bodies within the developing endosperm (Graham and Morton 1963). Protein accumulation is generally sigmoidal, and the rate of deposition in the linear phase is about 0.15-0.20 mg per day, with variation caused by factors such as genotype, nutrient availability and temperature (Stone and Nicolas 1996).

The metabolic proteins are the first to accumulate in appreciable amounts. Albumin and globulin together comprise approximately 90% of the total grain protein in the first 10 days of growth. The proportion of albumin and globulin in the total then declines so that they comprise about 20-30% at maturity (Stone and Savin 1999). The decline is due to the synthesis of storage proteins later in grain filling.

The gliadins are the first storage proteins to accumulate in measurable amounts, and they begin accumulating about 5-10 days after anthesis. From then until maturity, they typically accumulate at an average rate of about 0.1 mg per day (Stone and Savin 1999).

Glutenins are usually the last of the proteins to accumulate in the grain and may not be present in significant amounts until as late as 20 days after anthesis. From this time until maturity glutenins accumulate linearly and comprise a steadily increasing proportion of the total grain protein, reaching a maximum of 30-40% of the harvestable grain. The two solubility classes of glutenin (SDS soluble and insoluble) do not accumulate synchronously. The deposition of SDS-soluble glutenin tends to predominate early whereas SDS-insoluble glutenin tends to be synthesised late in grain filling (Stone and Savin 1999).

2.22 Response of yield and protein content to nitrogen availability

Addition of N fertiliser is one of the most-used tools for altering grain yield and quality. Its use is based upon the knowledge that it can increase grain yield, grain protein percent or both. If the available N is lower than that required for maximum grain yield, then a hyperbolic response to N fertiliser occurs (Figure 2.7).

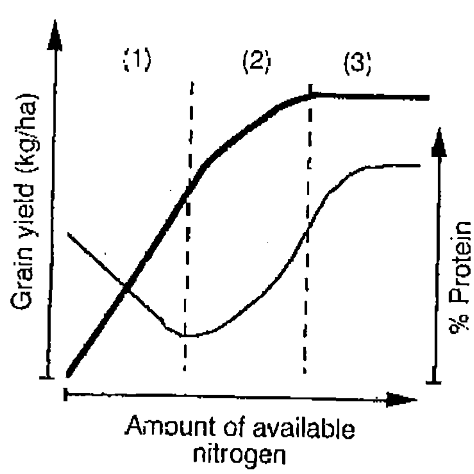

Figure 2.7 Diagrammatic representation of the response of yield and protein content to N fertiliser application.

Source: Stone and Savin (1999).

The first increment of N fertiliser applied increases the proportions of both carbohydrate and protein in the wheat grain, but the response of the carbohydrate fraction is usually a lot greater, resulting in a yield increase. This explains the frequently reported negative relationship of increased yield with decreased protein content after applying N early in crop development only. Application of more N fertiliser has less effect on carbohydrate accumulation but a greater effect on protein accumulation, with the net effect of a small yield increase and a large increase in grain protein content. In the third region of response the maximum yield has been achieved so more N produces no further carbohydrate accumulation. Protein accumulation is highly responsive to N in this 'luxury consumption' region, resulting in a large grain protein content increase (Stone and Savin 1999). Effective management is required to gain optimal results from N fertiliser applications. The timing and rate of N fertiliser application needs to be sufficient so that an optimum balance of maximum yield in the prevailing growing conditions and optimal quality are both attained. The effect of timing and rate of N fertiliser on wheat yield and quality was reviewed by Scott *et al.* (1992).

2.23 Key management issues for durum crops

Soil testing is often used to gauge the fertility status before a crop is sown. This allows any macronutrient deficiency to be rectified prior to crop establishment. To gauge the available soil N for a cereal crop, soil tests to 0.60 m depth are recommended (Stephen *et al.* 1997) but this may be inadequate on deep, free draining alluvial soils. The amount of N fertiliser that needs to be applied to a crop should complement the N available from the soil and be sufficient to allow the crop to achieve its yield potential. Assessment of the yield potential should allow for the limitations such as soil type and water availability. As with other wheats, adequate available N is required for durum wheat in the early stages of crop development so that optimal ear population and a high grain set can be achieved. Stephen *et al.* (1985) recommended applying N fertiliser at tillering to obtain maximum yield, by ensuring the optimum number of tillers survive to produce ears with high grain set.

N fertiliser applied late in the development of the crop (for example, flag leaf emergence) will ensure that adequate available N is present when grain protein accumulation begins after anthesis (Martin 1987). For New Zealand conditions, the amount of N applied late is usually about 20-60 kg N/ha (Scott pers.comm.) which is lot lower than the early application, as it is used solely to increase the protein content of the grain.

In addition to N fertility, the crop needs to be managed so that it is free from stresses caused by weed, pest, disease and water limitations, to minimise tiller death and ensure maximum photosynthetic area.

Durum wheat is particularly susceptible to pre-harvest sprouting if damp conditions occur. If wet conditions are forecast at harvest, harvesting when the grain moisture content is higher than 14% and then drying the grain is recommended. The susceptibility of certain cultivars to sprout damage is important information which the grower may use to prioritise harvesting, or decide on the costly process of harvesting early then drying the grain artificially.

2.24 Summary

For New Zealand durum wheat to compete with wheat grown overseas, growers must aim to produce high yielding crops of high quality grain to ensure optimum profit. Strategic use of N fertiliser is a key to achieving crops of optimal yield and quality. In the absence of other limiting factors, N fertiliser indirectly increases grain yield and protein content, and the latter is an important quality parameter.

Yield can be described in terms of yield components (Equation 1) which are determined continuously from the day the crop is sown. High grain yield is achieved by managing a crop to give a target grain population and to avoid the stresses which can shorten the duration of the crop canopy, such as N deficiency, water stress, lodging or disease.

Durum quality is a function of many interrelated parameters including protein content, α-amylase content, flour rheological properties and colour. Each parameter can be measured with a specific test and compared with standards. Standards are used to assess grain quality which determines the consequent end-use of the wheat. The effect of N availability on grain, flour and pasta quality parameters was reviewed in the present study with the aim of determining management guidelines for durum growers.

There are many types of protein in wheat with different chemical properties, and each one instils different rheological properties into the dough. However, growers are only paid for total protein content and no differentiation is made between protein fractions.

For New Zealand durum wheat an enhanced yellow/golden pasta colour is considered by consumers to be a desirable quality parameter. The carotenoid pigments within grains determine the yellow appearance of flour and pasta. The L*a*b colour space is the most appropriate system to measure the colour of durum grain, flour and pasta samples, due to its high correlation with human perception. Biochemical and physical factors which influence flour and pasta colour include disease exposure, grain and flour storage, milling extraction rate and pasta processing. However, the effect of agronomic N fertiliser treatments on grain, flour and pasta colour is unknown and its determination was a main objective in this study.

2.25 Research objectives

To investigate the effect that N fertiliser has on grain, flour and pasta colour by using different rates and timings of N fertiliser application on field trials in Canterbury.

To generate variability in grain yield and protein content using N management and two cultivars of durum wheat.

To determine differences in yield and quality of two durum wheat cultivars and establish if relationships exist between grain, flour and pasta colour.

CHAPTER 3 Materials and methods

3.1 Field experiment

3.1.1 Sites

Three sites in Canterbury with different physical and environmental conditions were selected to provide a range of potential grain yield and quality. Specifically, a dryland site at Darfield and two irrigated sites at Lincoln and Wakanui were used. The initial yield potential prior to any N application was predicted for each site. The Darfield site was predicted to have a yield potential of between 3 and 5 t/ha based on the available water holding capacity of between 64-102 mm/m of soil depth for the Templeton silt loam soil (Cox 1978) and an expected average season of rainfall. The Lincoln site at Crop & Food Research was also on a Templeton silt loam. It had irrigation but low N fertility, and an estimated moderate yield potential of between 4 and 5 t/ha due to the availability of irrigation. The third site was at Wakanui on an irrigated Wakanui silt loam soil with an available water holding capacity of over 100 mm/m of soil depth. It had previously grown a clover seed crop and was expected to have the highest yield potential of between 6 and 8 t/ha. These yield ranges were used to assist the determination of sowing rates and N application rates at establishment. It was predicted that the yield potential of each site could be increased with application of N fertiliser. Soil tests were carried out to determine the N status of the soil to confirm the expected yield potential for each site and assist the N management required to attain maximum yield and grain quality.

3.2 Soil testing

Soil samples were collected at each site to measure the macronutrient status and assist with determination of N fertiliser treatments. The soil was sampled at Wakanui on 14 August and at Darfield and Lincoln on 19 August 1999. A bulked sample of 10 soil cores was taken from depths of 0-0.15 m, 0.15-0.30, 0.30-0.45 m and 0.45-0.60 m as recommended by Stephen *et al.* (1997). The first 0.15 m section was analysed for pH, soil macronutrients (P, K, Ca, Mg, Na), CEC, (Table 3.1) P was determined by Olsen extraction and other nutrients were measured using standard quick tests. Available and total N contents (Table 3.2) were measured at each depth sampled. Available N in the cores from all depths was analysed using anaerobic incubation, followed by ammonium-N extraction using 2M potassium chloride (Keeney and Bremner 1967). The total nitrogen of the sample was measured using Kjeldahl digestion.

Table 3.1 Macronutrient and pH status of soil from 0.15 m cores taken from three experimental sites in August 1999.

Test	Darfield	Lincoln	Wakanui	Optimal range
pH	5.6	5.9	6.6	5.8-6.2
P (μg/ml)	13	18	21	20-30
K (g/250 L)	0.31	0.50	0.30	0.5-0.8
Ca (g/ 40 L)	6.3	5.8	11.6	5.0-12.0
Mg (g/1,000 L)	0.69	0.51	0.92	0.8-3.0
Na (g/1,000 L)	0.07	0.1	0.14	0.0-0.5
Cation exchange capacity	13.1	12.0	14.8	12-25

Note: Optimal ranges by R.J Hill Laboratories Ltd.

Table 3.2 Available N (kg/ha) and total soil N (%) status from soil cores taken from three experimental sites in August 1999.

	Darfield		Lincoln		Wakanui	
Depth (m)	Available N	Total N	Available N	Total N	Available N	Total N
0-0.15	79	0.22	65	0.18	96	0.16
0.15-0.30	76	0.22	45	0.16	80	0.12
0.30-0.45	49	0.10	23	0.12	38	0.08
0.45-0.60	38	0.08	16	0.06	22	0.04
Total (0-0.60)	242		149		236	

3.3 Climate

The climate in Canterbury is characterised by an annual rainfall of about 670 mm, which is slightly higher in winter than other seasons (MetService 1983). The annual mean temperature is 11.4°C varying from a monthly average of 6.0°C in July to 16.8°C in January. Summer is warm with occasional temperatures above 30°C. Winter is cool with frequent frosts and occasional snow.

The 1999-2000 growing season was wet compared with the previous two years. In particular, January was from 30 to 70 mm wetter than the long term mean of 50 mm (Table 3.3).

Table 3.3 Monthly rainfall (mm) recorded at the three experimental sites during the 1999/2000 growing season and the long term mean (LTM) records for Lincoln.

Month	Darfield 1999	Lincoln 1999	Wakanui 1999	LTM
August	46	58	27	68
September	21	27	36	40
October	55	51	70	55
November	111	61	99	56
December	40	35	86	61
January	79	85	122	50
February	49	19	31	51

3.4 Experimental design

A field experiment was carried out at each site. The same randomised complete block factorial design was sown with four replicates of 12 treatments comprising two durum cultivars ('CRDW17' and 'Waitohi') and six N application treatments (Table 3.4). The amount of N applied differed among sites but followed the same basic pattern of none or some during early tillering (GS23, (Zadoks *et al.* 1974)) and three rates at flag leaf emergence (GS39) (Table 3.4). Treatments were designed to provide ranges of grain yields and protein contents. All N was applied as calcium ammonium nitrate (CAN).

Table 3.4 Rates of N fertiliser (kg N/ha) applied in the six treatments at the three sites at two growth stages (tillering and flag leaf emergence).

Treatment No.	Darfield (kg N/ha)		Lincoln (kg N/ha)		Wakanui (kg N/ha)	
	GS23	GS39	GS23	GS39	GS23	GS39
1	0	0	0	0	0	0
2	150	0	175	0	150	0
3	150	25	175	40	150	50
4	150	50	175	80	150	100
5	0	25	0	40	0	50
6	0	50	0	80	0	100

3.5 Seed

The seed for both cultivars was obtained from Crop & Food Research and was treated with Baytan (triadimenol and imazalil) and Fuberidazole fungicides at label rates, before it was sown. Germination tests showed 100% germination for 'CRDW17' and 94% for 'Waitohi'. The thousand grain weight for 'CRDW17' was 60 g compared with 50 g for 'Waitohi'. Based on these figures, sowing rates were adjusted to achieve a mean target population of 250 plants/m^2.

3.6 Site preparation and crop husbandry

3.6.1 Darfield

The previous turnip crop was fed off as winterfeed and then the site was ploughed on 9 August 1999. This was followed by multi-tyne cultivation on 12 August. The experiment was sown on 13 August with a plot size of 15 x 1.35 m using an Øyjord cone drill with rows 0.15 m apart.

No N was applied at sowing. However, 150 kg N/ha was applied during tillering in the fertilised treatments (Table 3.4). Split applications were used, with 50 kg N/ha on 17 September, a further 75 kg N/ha on 1 October, and the final 25 kg N/ha on 4 November. Late applications of 25 or 50 kg N/ha were applied to the fertilised treatments at flag leaf emergence which occurred on 22 November. Thus, the total amount of N applied ranged from 0 to 200 kg/ha (Table 3.4). At all sites, applications were made by evenly spreading individual weighed amounts of fertiliser on the plots by hand.

A mixture of herbicides including Glean (7.5 g/ha chlorsulfuron), Cougar (1 g/ha diflufenican and 5 g/ha isoproturon) and MCPA (375 g/ha 4-chloro-2-methyl phenoxy acetic acid) was applied on 30 September to control the main weed population of californian thistles (*Cirsium arvense*), wireweed (*Polygonum aviculare*) and field pansy (*Viola arvensis*). This was followed by Puma (45 g/ha fenoxaprop-P-ethyl) to control the wild oat (*Avena fatua*) population, Mavrik (9.6 g/L tau-fluvalinate) was also applied in this application on 8 November to control aphid numbers. Fungicide applications included

Opus (125 g/ha epoxiconazole) on 20 October (GS32) and Folicur (190 g/ha terbuconazole) on 8 November (GS32-3) followed by two applications of Opus and Cereous (125 g/ha triadimenol) on 24 November (GS39) and 15 December (GS61) to control stripe rust, leaf rust, speckled leaf blotch and powdery mildew.

3.6.2 Lincoln

After the previous crop of potatoes was harvested, the site was sprayed with Roundup (1.9 kg/ha glyphosphate) and Dicamba (100 g/ha dicamba) on 3 March 1999. This was followed by deep ploughing on 12 May and deep grubbing on 16 July. The site was rotocrumbled, harrowed and rolled on 26 August before the experiment was sown with an Øyjord cone drill on 27 August. The plot size was 12 x 1.35 m with 0.15 m row spacing.

The first application of fertiliser treatments was 175 kg N/ha during tillering (Table 3.4). Again, split applications were used, consisting of 50 kg N/ha on 17 September, 75 kg N/ha on 1 October and, finally 50 kg N/ha on 4 November. Late applications of 40 or 80 kg N/ha were applied to the fertilised treatments at flag leaf emergence on 17 November. Thus, the total amount of N applied ranged from 0 to 255 kg N/ha (Table 3.4).

A total of 160 mm of water was applied by irrigation over the growing season to maintain a soil moisture deficit of less than 100 mm in the top metre of soil. Three applications of 60 mm on 29 November, 50 mm on 13 December, and 50 mm on 19 January 2000 were made using a lateral spray irrigator. Glean (15 g/ha chlosulfuron) was applied pre-emergence on 3 September, and Cougar (100 g/ha diflufenican and 500 g/ha isoproturan) was applied post-emergence on 8 October to control weeds. Pirimor 50 was applied at 125 g/ha pirimicarb on 12 October for aphid control. Fungal diseases were controlled by Folicur (190 g/ha terbuconazole) applied on 12 October (GS30) and Cereous (125 ml/ha tridimenol) on 17 November (GS39).

3.6.3 Wakanui

The site was ploughed on 27 August 1999 and power harrowed on 29 August. The experiment was sown on 30 August with an Øyjord cone drill with a plot size of 12 x 1.35 m and 0.15 m row spacing.

At sowing 50 kg N/ha was applied to the whole paddock, including the trial area, so the zero N treatment actually included a base dressing of 50 kg N/ha. In the treatments fertilised during tillering 150 kg N/ha was applied in split applications of 100 kg N/ha on 26 September and 50 kg/ha on 10 October. Late N at 50 or 100 kg N/ha was applied to the fertilised treatments at flag leaf emergence on 18 November.

The availability of irrigation enabled 135 mm of water to be applied over the growing season to maintain a soil moisture deficit of less than 100 mm in the top 1 m of soil. It was applied in three applications of 45 mm on 30 October, 9 December and 22 December.

Cougar (400 g/ha diflufenican and 200 g/ha isoproturon) was applied post-emergence on 25 September to prevent weed establishment in the crop. A further herbicide application of Bromoxynil (Bromoxynil 160 g/ha), Duplosan KV (420 g/ha mecoprop-P) and Glean (5.25

g/ha chlorsulfuron) was applied on 19 October (GS30). Topik (16.8 g/ha clodinafop-propargyl) was applied on 29 October to control the wild oat population. Foliar fungal disease control included an initial application of Merit (94 g/ha propiconazole and 280 g/ha fenpropimorph) on 7 November (GS37) with a second application on 21 November (GS39) which was included in a mixture with Amistar (188g/ha azoxystrobin). The final fungicide application of Merit on 10 December (GS60) also included Amistar.

3.7 Crop growth and yield

3.7.1 Measurements

Plant populations were counted in three random 0.1 m^2 quadrats per plot at coleoptile emergence, and results showed that the target population of 250 plants/m^2 was achieved uniformly across the experimental area at each site. Above ground biomass cuts (2 x 0.1m^2) were taken from three replicates of each experiment at flag leaf emergence (GS39). This occurred on 22 November at Darfield, 17 November at Lincoln and 18 November at Wakanui. The fresh weight was determined and the samples were oven dried at between 60 to 70°C for 24 hours. Sub samples of approximately 50 g were taken of the fresh material and dried separately. The final dry weight was recorded and the dry matter content for each plot was calculated. The dried sub sample was ground using a Cyclotec 1093 sample mill with a 1mm sieve and then analysed for total N content using Kjeldahl digestion.

A final biomass cut (2 x 0.1 m^2) was taken when the crop was at physiological maturity on

9 February at Darfield and Lincoln and 29 February at Wakanui. The fresh and dry weights and percentage dry matter were determined, and the number of ears in each 0.1 m^2 quadrat was counted. Sub-samples of 50 g where taken from the fresh material and dried separately from each plot in one rep. The N content for the vegetative part of the sub-sample (i.e without the ear) was determined using Kjeldahl digestion.

Durum wheat is very susceptible to sprouting and the weather was dull and moist at all sites in the period leading up to harvest maturity. To ensure that some unsprouted grain would be available for quality tests, a one m^2 sample was harvested by hand from each plot on 14 February at Darfield and Lincoln. The Wakanui site had not reached physiological maturity at this time, so hand harvested sampling was not possible.

The rest of the plots at Darfield and Lincoln were combine harvested on 21 February and on 2 March at Wakanui. Grain was dried in hessian sacks on a forced air drying floor to a moisture content of 14%. The hand harvested samples were put through a Kurtpelz thresher to separate the grain from the vegetative component of the wheat, and the grain was dried to 14% moisture content.

3.8 N measurement

At all sites, soil N tests were taken prior to sowing (Table 3.2) to a depth of 0.60 m. In addition, final soil tests were taken from four 'CRDW17' treatments (1, 2, 4 and 6) from one rep at each site when the crop reached physiological maturity.

Vegetative (excluding ear) N content was determined from dry matter cuts taken at physiological maturity from one rep at each site using Kjeldahl digestion. The protein content of harvested grain was measured and the grain N content was derived from the protein values. A nitrogen budget was constructed for each site (Tables 4.4, 4.5 and 4.6) by reconciling the N content of the grain and vegetative biomass with expected inputs from soil and fertiliser N. No statistical analysis was possible as only a single replicate from each site was measured.

3.9 Grain quality measurements

Grain quality testing was carried out on both hand harvested and header harvested samples. All grain was passed through a Rotoscreen with a 2 mm sieve to determine the percentage screenings in the sample. The thousand grain weight (TGW) was determined for each sample after counting 1000 grains with a Numigral seed counter. A 10 g sample of the grain was milled to wheatmeal (flour and bran) with a Perten laboratory mill 3100, and the protein and moisture contents were measured with a Technicon Infra Alyzer 450 (NIR) (Method 39-11, AACC 1983). From the milled sample 7 g was mixed with 25 mL of distilled water in a test tube and mixed thoroughly. The degree of sprout damage was assessed by running the sample through the Falling Number 1600 apparatus (Method 56-81B, AACC 1983).

A Minolta CR-210 chroma meter (Plate 1) calibrated to a standard white tile (L* = 98.07, a* = -6.23, b* = 1.88) was used to obtain triplicate L*a*b* readings for each grain sample at each site. Readings were taken under standard fluorescent light conditions, with grain

A Minolta CR-210 chroma meter (Plate 1) calibrated to a standard white tile ($L^* = 98.07$, $a^* = -6.23$, $b^* = 1.88$) was used to obtain triplicate $L^*a^*b^*$ readings for each grain sample at each site. Readings were taken under standard fluorescent light conditions, with grain placed in a 20 mm deep glass petrie dish on non-shiny black paper as outlined by Penno (1996).

Plate 1. A Minolta CR-210 Chroma Meter

3.10 Flour testing

Prior to milling, the grain was tempered to 16% moisture content. Grain from three replicates at each site was passed through a Brabender® test mill quadrumat® junior with an average extraction rate of 40%. The hand harvested m^2 samples from Darfield and the Buhler mill had an average extraction rate of 60%. After milling all flour samples were stored at 4°C.

Flour quality tests were carried out on all milled samples. These included moisture and protein contents by NIR and Falling Number as described previously (Section 3.9). Flour colour was also quantified using the Minolta chroma meter CR 300 using a standardised cell ($L^* = 97.14$, $a^* = 4.79$, and $b^* = 6.97$) as a reference.

Water absorption was determined by running 50 g flour samples through a Brabender farinograph (Method 54.21, AACC 1983). This also allowed determination of dough development time and dough stability time. Both dough development time and dough stability time results are presented as minute values as this is used in industry instead of SI units.

The carotenoid pigment content of the flour samples which were extruded to pasta (two replicates at Darfield and one at Lincoln) were determined. Pigments were extracted and measured from an 8.0 g flour sample using water saturated butyl alcohol (Method 14-50, AACC 1995).

3.11 Pasta extrusion and quality testing

Machine harvested samples from two replicates at Darfield and one replicate at Lincoln were milled and extruded. Each sample took two hours to extrude to pasta, which is why the sample number was limited to only 36 in total. No Wakanui samples were extruded as the sprout damage was considered too severe and unrepresentative of what would occur in industry.

The flour was tempered to 35% moisture content using water at 40°C and was then mixed mechanically in the extruder for 15 minutes. Pasta was extruded in the form of lasagne sheets using a La Parmigiana mini extruder. After extrusion the sheets were dried to 12% moisture content in a pre-dry 55°C oven for four hours on wire mesh trays. About 10 g of dried pasta was ground using a Retsch ZM 100 Ultra Centrifugal Mill and then the moisture contents were determined using NIR. The L*a*b* values were also quantified by placing the dried lasagne sheets on top of the Minolta chroma meter CR-300 under standard fluorescent light conditions.

3.12 Statistical analyses

A full factorial design was used for all analyses of variance (ANOVA) using Minitab (Minitab 1989) and mean separation was based on Fisher's protected least significant difference tests at $\alpha<0.05$.

Chapter 4
Results

There were no three-way interactions unless stated. Full interaction table and figures are presented for completeness and continuity, where no two or three way interactions occurred any main effect responses are described. Significant interactions and main effects are listed in the tables.

4.1 Yield and yield components

4.1.1 Darfield

4.1.1.1 Yield

There were no significant two-way interactions between the effects of cultivar and N treatments for grain yield, total dry matter (TDM) yield or harvest index (HI). However, grain yield was increased ($p<0.001$) from at least 3.5 to over 5.5 t/ha by the sole application of 150 kg/ha of N at tillering for both cultivars (Figure 4.1a). There was no significant yield increase from the late N applications for either cultivar regardless of early N status. In contrast, the TDM was increased ($p<0.001$) by both the early N alone and late N applications and these responses were independent of cultivar (Figure 4.1b). The early N application increased ($p<0.001$) TDM from 8.5 to over 12 t/ha, and 80 kg N/ha applied at flag leaf emergence produced a further 2 t/ha increase ($p<0.001$). The combination of changes in grain and biomass yields caused by the early N application led to a decrease ($p<0.05$) in HI from 40 to 32% for 'Waitohi' and from 36 to about 32% for 'CRDW17' (Figure 4.1c). However, the cultivar differences were not significant.

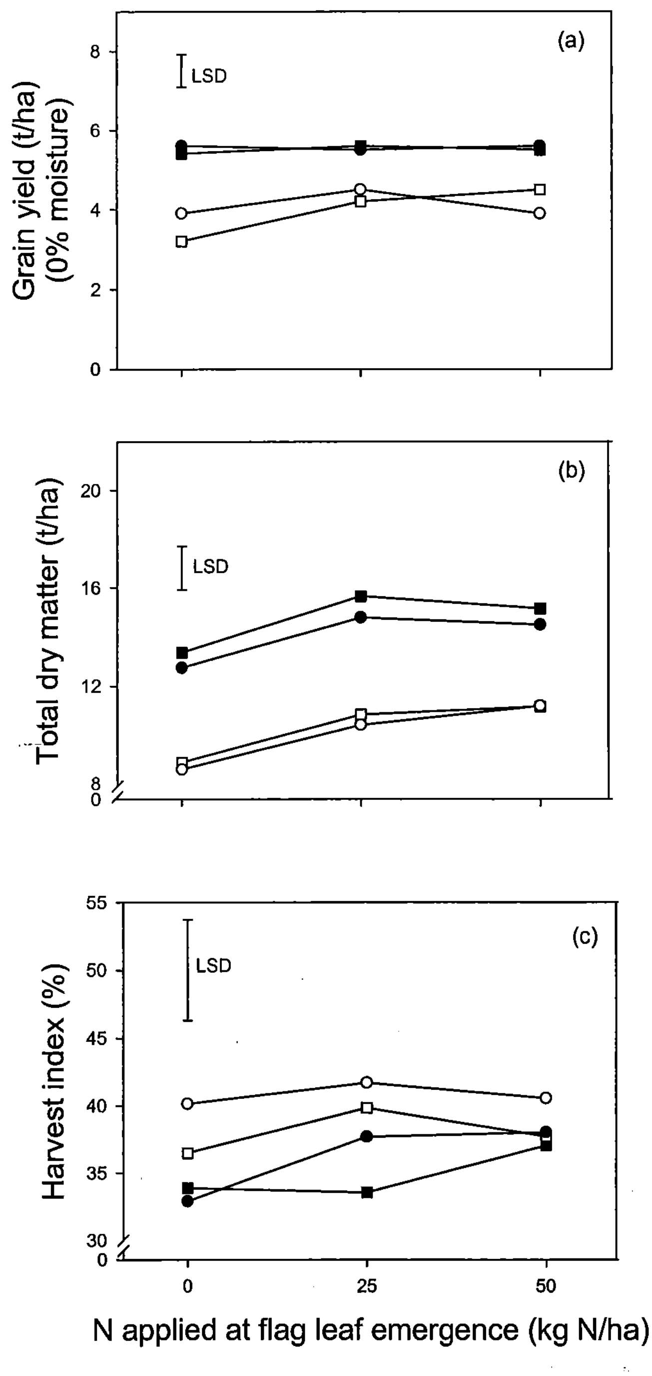

Figure 4.1 Mean grain yield (a) (at 0% moisture), total dry matter (b) and harvest index (c) values for 'CRDW17' ( ) and 'Waitohi' (●) against late N application (flag leaf emergence) rate after early N (tillering) had been applied at 150 kg N/ha (closed symbols) or not at all (open symbols) for crops grown at Darfield. LSD represents error for the three-way interaction.

4.1.1.2 Components of yield

Despite the consistency in grain yield, the yield components were affected by the treatments (Table 4.1). The number of ears/m^2 was influenced by the interaction ($p < 0.001$) of early and late N applications and by the main effect of cultivar. The application of 50 kg N/ha at flag leaf emergence increased the number of ears/m^2 from 630 to 1030 for 'CRDW17' and from 540 to 820 for 'Waitohi'. In contrast the population decreased when 150 kg N/ha was applied at tillering followed by the 50 kg N/ha at flag leaf emergence. Overall 'CRDW17' produced 825 ears/m^2 which was higher ($p<0.001$) than for 'Waitohi' (690) (Table 4.1).

The mean number of grains/ear increased ($p<0.001$) from 9.4 to 13.6 with the addition of only early N and was lower ($p<0.001$) for 'CRDW17' (9.7) than 'Waitohi' (13.4) (Table 4.1).

The combined effect of varying ears/m^2 and grains/ear resulted in a similar number of grains/m^2 for both cultivars, but this was increased ($p<0.001$) from about 7000/m^2 to 10000/m^2 by the addition of early N (Table 4.1).

For TGW there was an interaction ($p<0.01$) between the effects of cultivar and early N application. The mean TGW of 'CRDW17' decreased from about 60 to 53 g when 150 kg N/ha was applied early, whereas the magnitude of the decrease was smaller for 'Waitohi' which fell from about 55 to 53 g (Table 4.1).

Table 4.1 Mean values of yield components (ears/m^2, grains/m^2 and thousand grain weight (TGW)) for 'CRDW17' and 'Waitohi' durum wheat grown at Darfield with different N fertiliser treatments.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Ears/m^2	Grains/ear †	Grains/m^2 †	TGW (g)
'CRDW17'	0	0	630	8.6	5395	60.0
	0	25	970	7.0	6825	61.2
	0	50	1030	7.4	7570	59.5
	150	0	1000	10.5	10310	53.3
	150	25	770	13.7	10500	52.5
	150	50	970	11.0	10530	52.5
Mean	-	-	895	9.7	8521	56.5
'Waitohi'	0	0	540	13.1	7120	54.3
	0	25	710	11.2	7800	57.6
	0	50	820	9.3	7035	55.5
	150	0	720	14.9	10505	53.5
	150	25	710	14.5	10240	54.1
	150	50	630	17.1	10735	52.4
Mean	-	-	688	13.4	8906	54.6
SE max			71.7	1.27	576.1	1.39
Significance * = 0.05 ** = 0.01 ***=0.001			L* CV*** E*L**	E*** CV***	E***	E*** CV* CV*E**

(† represents values derived by calculations from other yield components)

4.1.2 Lincoln

4.1.2.1 Yield

Grain yield at Lincoln was affected ($p<0.05$) by the interaction of early and late nitrogen but not by cultivar. The addition of only the 175 kg N/ha at tillering increased the grain yield from about 4.5 t/ha to over 7 t/ha (Figure 4.2a) and for these crops the additional N at flag leaf emergence did not lead to a grain yield increase. In contrast, the addition of 40 and 80 kg N/ha at flag leaf emergence produced a linear increase ($p<0.001$) in yield for crops that had not received the N at tillering (Figure 4.2a).

Despite the similar trends observed for TDM the interaction was not significant (Figure 4.2b). However, the addition of only early N did lead to an increase ($p<0.001$) of about 4 t/ha for both cultivars with no further increase from late N. Again 80 kg of late N increased TDM when no early N was applied, although this was not significant. Even with these differences, N treatment did not affect HI, although the HI for 'CRDW17' (46%) tended to be lower than for 'Waitohi' (49%) (Figure 4.2c).

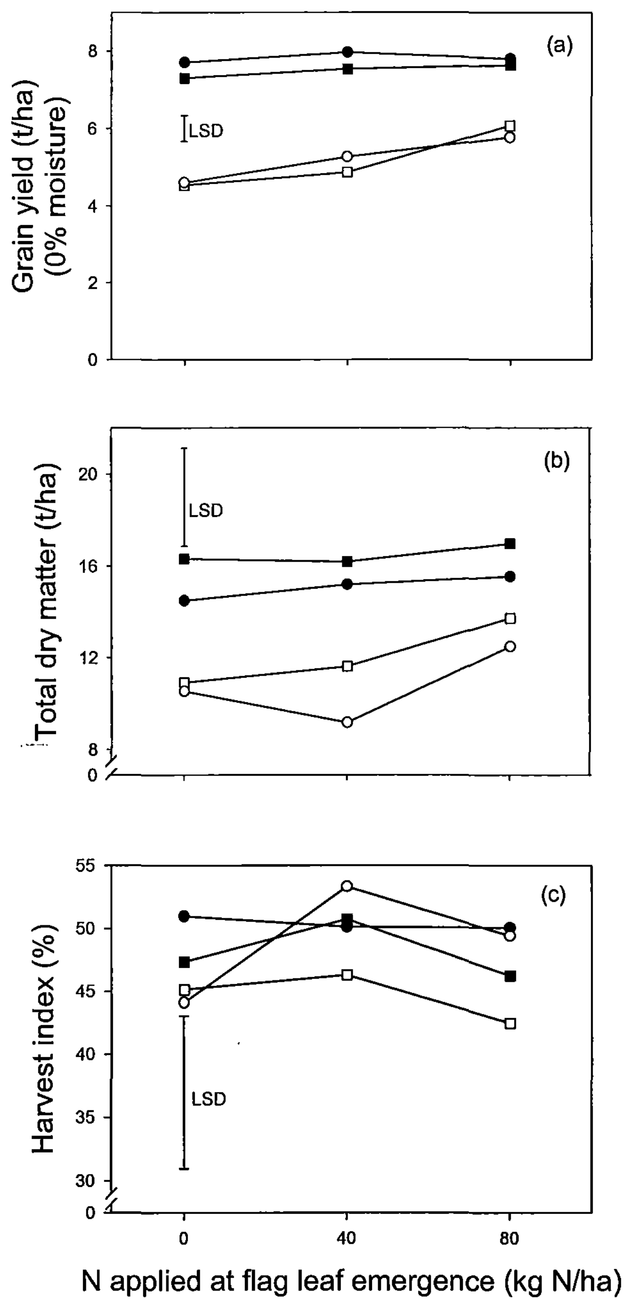

Figure 4.2 Mean grain yield (a) (at 0% moisture), total dry matter (b) and harvest index (c) values for 'CRDW17' ( ) and 'Waitohi' (●) against late N application (flag leaf emergence) rate after early N (tillering) had been applied at 175 kg N/ha (closed symbols) or not at all (open symbols) for crops grown at Lincoln. LSD represents error for the three-way interaction.

4.1.2.2 Components of yield

The components of yield were also affected by treatments but the effect differed for each component (Table 4.2). The number of ears/m^2 was only affected ($p<0.01$) by late N as a main effect. For all crops that had no early N applied, 80 kg N/ha applied late produced a linear increase from 685 to about 1100 ears/m^2 and by about 100 ears/m^2 when early N had been applied.

The mean number of grains/ear was influenced by early N ($p<0.001$) and cultivar ($p<0.001$) main effects. For 'CRDW17' the number of grains/ear increased from 8.9 to 12.6 with early N and from 11.3 to 16.1 for 'Waitohi'. The result was less grains/ear for 'CRDW17' (10.7) than for 'Waitohi' (13.7).

For TGW, there was an interaction ($p<0.01$) between the effects of cultivar and early N. TGW was stable for 'CRDW17' but increased by about 2 g with the addition of early N for 'Waitohi'.

The combined effect of ears/m^2 and grains/ear, grains/m^2 resulted in being influenced by the interaction ($p<0.05$) of early and late N applications and differed between cultivars. Specifically, the application of late N to the zero early N treatments increased the number of grains/m^2, but there was no effect of late N when early N had been applied. In addition, the mean number of grains/m^2 for 'Waitohi' (10992) was higher ($p<0.001$) than for 'CRDW17' (9584) (Table 4.2).

Table 4.2 Mean values of yield components (ears/m^2, grains/m^2 and thousand grain weight (TGW)) for 'CRDW17' and 'Waitohi' durum wheat grown at Lincoln with different N fertiliser treatments.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Ears/m^2	Grains/ear†	Grains/m^2†	TGW (g)
'CRDW17'	0	0	690	10.4	6755	68.1
	0	40	845	9.2	7680	68.5
	0	80	1170	7.3	8410	68.7
	175	0	900	12.9	11480	67.1
	175	40	965	13.0	11610	68.7
	175	80	995	11.8	11570	67.5
Mean	-	-	928	10.7	9584	68.1
'Waitohi'	0	0	685	12.2	8090	56.1
	0	40	790	11.0	8610	56.5
	0	80	1035	10.8	10715	56.7
	175	0	770	16.6	12500	58.4
	175	40	780	16.5	12780	58.9
	175	80	885	15.1	13260	57.6
Mean	-	-	824	13.7	10992	57.4
SEmax			90.6	1.11	426.1	0.74
Significance * = 0.05 ** = 0.01 *** = 0.001			L**	E*** CV***	E*** L*** CV*** E*L*	CV*** CV*E**

(† represents values derived by calculations from other yield components)

4.1.3 Wakanui

4.1.3.1 Yield

In contrast to the other sites, the grain yield of crops at Wakanui was affected by the interaction ($p<0.05$) between cultivar and early N but there was no effect of late N. For 'CRDW17', grain yield decreased by about 1 t/ha with the early N application but there was a small increase for 'Waitohi' (Figure 4.3a).

For TDM there was an interaction ($p<0.05$) between cultivar and early N and a late N main effect (Figure 4.3b). Specifically, the early N only treatment increased the TDM for 'Waitohi' from about 16 t/ha to over 20 t/ha but there was no increase for 'CRDW17'. However, late N also increased ($p<0.05$) TDM until there were no differences in TDM from any treatments when 100 kg N/ha was applied late. For HI there was only a main effect of early N application. For both cultivars, early N application decreased ($p<0.05$) the mean HI from 43% to 40% (Figure 4.3c).

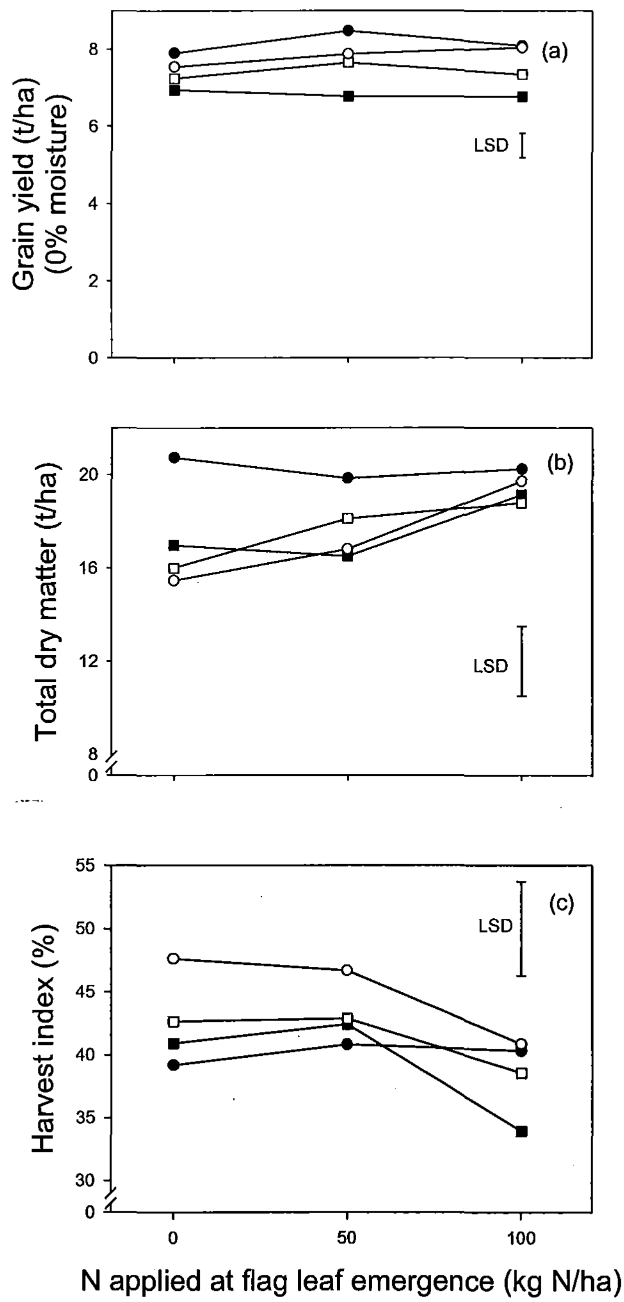

Figure 4.3 Mean grain yield (a) (at 0% moisture), total dry matter (b) and harvest index (c) values for 'CRDW17' ( ) and 'Waitohi' (●) against late N application (flag leaf emergence) rate after early N (tillering) had been applied at 150 kg N/ha (closed symbols)or not at all (open symbols) for crops grown at Wakanui. LSD represents error for the three-way interaction.

4.1.3.2 Components of yield

The number of ears/m^2 was increased ($p< 0.001$) by between 300 and 600 ears/m^2 by only early N application for both cultivars (Table 4.3). In contrast, the mean number of grains/ear decreased ($p<0.01$) with the addition of early N, with a lower ($p<0.001$) mean number for 'CRDW17' (9.8) than 'Waitohi' (12.5) (Table 4.3).

The number of grains/m^2 was affected by the interaction ($p<0.05$) between cultivar and early N application with consistent numbers across nitrogen treatments for 'CRDW17' but an increase for 'Waitohi' crops that had received early N (Table 4.3).

For TGW the interaction ($p<0.01$) of cultivar and late N showed a decrease in TGW with increasing late N for 'CRDW17' but no effect of late N for 'Waitohi' (Table 4.3). In addition, early N as a main effect decreased ($p<0.001$) the TGW for both cultivars.

Table 4.3 Mean values of yield components (ears/m^2, grains/m^2 and thousand grain weight (TGW)) for 'CRDW17' and 'Waitohi' durum wheat grown at Wakanui with different N fertiliser treatments.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Ears/m^2	Grains/ear†	Grains/m^2†	TGW (g)
'CRDW17'	0	0	1150	10.6	12010	56.7
	0	50	1280	11.1	14275	53.9
	0	100	1370	10.5	13970	51.9
	150	0	1420	9.3	12960	53.5
	150	50	1450	8.7	12680	52.1
	150	100	1650	8.5	13880	48.8
Mean	-	-	1386	9.8	13296	52.8
'Waitohi'	0	0	960	15.2	14500	52.7
	0	50	1105	13.3	14715	53.1
	0	100	1300	12.0	15385	52.3
	150	0	1575	10.6	16390	48.3
	150	50	1520	10.7	15830	50.7
	150	100	1355	13.3	16370	49.1
Mean	-	-	1302	12.5	15531	51.0
SEmax			82.9	0.81	479.4	0.87
Significance * = 0.05 ** = 0.01 *** = 0.001			E***	E** CV***	CV*** CV*E*	CV** E*** L* CV*L**

(† represents values derived by calculations from other yield components)

4.2 Nitrogen budget

4.2.1 Darfield

The soil test prior to sowing showed that available soil N to 0.60 m depth was 242 kg N/ha (Table 3.2).

The N content of the vegetative biomass ranged from 0.32 to 1.08% N, and corresponding N yields were between 16-99 kg N/ha (Table 4.4). When early N was applied, vegetative biomass N contents were 0.10 to 0.65% higher than when no early N was applied. Over all treatments, 'Waitohi' had a mean content of 0.46% compared with 0.76% for 'CRDW17'. In addition, the mean grain N content for 'Waitohi' (1.98%) was higher than for 'CRDW17' (1.83%), and this difference translated into higher grain protein percentage values (Section 4.3.2).

Three of the four final soil tests indicated that there was 10-50 kg/ha more N in the soil profile than was predicted from the N budget estimates. The exception was when a total of 200 kg N/ha was applied to 'CRDW17'. In that case the predicted residual soil N was 224 kg N/ha compared to a measured value of 200 kg N/ha (Table 4.4).

Table 4.4 Vegetative N content, grain N content and final soil N for two durum wheat cultivars ('CRDW17' and 'Waitohi') grown at Darfield. N was applied early (tillering) and late (flag leaf emergence) at different rates. These values were used to calculate total grain and vegetative N yield and to estimate an N balance.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Vegetative biomass (%N)	Vegetative N (kg/ha)	Grain (%N)	Grain N (kg/ha)	Measured final soil N (kg/ha)	Estimated N balance (kg/ha)
'CRDW17'	0	0	0.36	22	1.52	49	206	171
	0	25	0.38	25	1.65	69	201	173
	0	50	0.97	73	1.67	75	-	144
	150	0	0.89	76	1.94	105	223	211
	150	25	0.85	83	2.05	115	-	220
	150	50	1.08	99	2.16	119	200	224
Mean	-	-	0.76	63	1.83	89	208	191
'Waitohi'	0	0	0.39	23	1.55	60		159
	0	25	0.34	21	1.78	80		166
	0	50	0.32	16	1.94	76		200
	150	0	0.45	28	2.16	121		243
	150	25	0.67	52	2.14	119		247
	150	50	0.59	44	2.30	129		269
Mean	-	-	0.46	31	1.98	98		214

* The initial available soil N was 242 kg/ha.

4.2.2 Lincoln

The initial available soil N value was 149 kg N/ha. The range of vegetative N content (0.29 to 1.22%) was similar to Darfield and followed similar trends. The large range in N content and biomass yields led to a range of vegetative N yields of 18-112 kg N/ha (Table 4.5). Again, the mean vegetative N content of 'Waitohi' (0.53%) was lower than 'CRDW17' (0.72%) and the grain N content for 'Waitohi' (1.98%) was higher than for 'CRDW17' (1.88%).

When early N was applied the final measurement of available soil N was within 30 kg N/ha of the calculated N value. However, when no early N was applied the measurement value was between 70 and 100 kg N/ha higher than the calculated value (Table 4.5).

Table 4.5 Vegetative N content, grain N content and final soil N for two durum wheat cultivars ('CRDW17' and 'Waitohi') grown at Lincoln. N was applied early (tillering) and late (flag leaf emergence) at different rates. These values were used to calculate total grain and vegetative N yield and to estimate an N balance.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Vegetative biomass (%N)	Vegetative N (kg/ha)	Grain (%N)	Grain N (kg/ha)	Measured final soil N (kg/ha)	Estimated N balance (kg/ha)
'CRDW17'	0	0	0.41	26	1.65	76	142	47
	0	40	0.56	36	1.74	92	133	62
	0	80	0.43	35	1.87	108	-	86
	175	0	0.86	74	1.92	147	133	102
	175	40	0.82	68	2.04	162	-	134
	175	80	1.22	112	2.03	158	130	134
Mean	-	-	0.72	59	1.88	124	135	94
'Waitohi'	0	0	0.29	18	1.62	73		58
	0	40	0.46	20	1.85	90		79
	0	80	0.56	36	2.06	123		68
	175	0	0.49	35	2.00	146		143
	175	40	0.68	52	2.08	157		155
	175	80	0.72	57	2.27	173		174
Mean	-	-	0.53	36	1.98	127		113

* The initial available soil N was 149 kg/ha.

4.2.3 Wakanui

The initial available soil N value was 236 kg N/ha. The vegetative N content was higher than at the other two sites, with a range of values from 0.55 to 1.42% resulting in removal of between 42 and 137 kg N/ha (Table 4.6). The same trend was observed at Wakanui as at the other sites whereby 'Waitohi' (0.65%) had a lower mean vegetative N content than 'CRDW17' (0.96%), but a higher mean grain N content (2.1%) than 'CRDW17' (1.9%).

For all cases except when the highest total N rate was applied, the final soil N was higher than the value calculated with the N budget. The exception was when a total of 350 kg N/ha was applied and the measured value was 50 units lower than the calculated value (Table 4.6).

Table 4.6 Vegetative N content, grain N content and final soil N for two durum wheat cultivars ('CRDW17' and 'Waitohi') grown at Wakanui. N was applied early (tillering) and late (flag leaf emergence) at different rates. These values were used to calculate total grain and vegetative N yield and to estimate an N balance.

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Vegetative biomass (%N)	Vegetative N (kg/ha)	Grain (%N)	Grain N (kg/ha)	Measured final soil N (kg/ha)	Estimated N balance (kg/ha)
'CRDW17'	50	0	0.69	63	1.70	116	215	107
	50	100	0.55	57	1.90	146	260	134
	50	150	1.21	137	1.92	140		109
	200	0	0.87	87	1.97	136	218	213
	200	100	1.42	128	2.08	141		217
	200	150	1.00	132	2.08	141	210	263
Mean	-	-	0.96	101	1.94	137	226	174
'Waitohi'	50	0	0.58	42	1.85	141		103
	50	100	0.58	52	2.03	158		125
	50	150	0.58	66	2.14	172		148
	200	0	0.71	90	2.23	177		169
	200	100	0.65	77	2.13	171		238
	200	150	0.80	56	2.30	185		295
Mean	-	-	0.65	64	2.11	167		180

* The initial available soil N was 236 kg/ha

4.3 Grain Quality

4.3.1 Falling number

The grain samples that were harvested by hand a week early had higher mean falling numbers than the combined samples for both cultivars at both Darfield and Lincoln (Table 4.7). The mean falling numbers at Darfield were 262 and 151 s for 'CRDW17' and 307 and 170 s for 'Waitohi' for the hand harvested and combine harvested samples respectively. Trends were similar at Lincoln, with mean values of 194 and 118 s for 'CRDW17' and 282 and 215 s for 'Waitohi'.

At Wakanui, early harvest was not possible because the crops were still immature (GS85), and so all plots were combine harvested on 2 March. The mean falling number for 'CRDW17' was 81 s and 122 s for 'Waitohi'.

At each site there was a strong cultivar effect with falling number values for 'CRDW17' lower ($p<0.05$) than 'Waitohi' in both the hand and combine harvested plots (Table 4.7). Except for the hand harvested samples at Darfield, the magnitude of the difference was also affected by an interaction with the N treatments. For the combine harvested samples at Darfield, the falling number values for 'CRDW17' were decreased by 20 to 70 s after early N but for 'Waitohi' the reduction was 50 to 100 s. At Lincoln the falling number of the hand harvested samples of 'CRDW17' increased ($p<0.05$) from about 164 to 223 s after early N application (Table 4.7) but it was about 280 s regardless of early N status for 'Waitohi'. Also at Lincoln, combine harvested samples showed the same trend with early

N decreasing ($p<0.001$) the mean falling number for 'Waitohi' more than for 'CRDW17' (Table 4.7). Similarly, at Wakanui the falling number for 'CRDW17' decreased from 86 to 75 s following 150 kg N/ha applied early with a sharper decrease from 158 to 86 s for 'Waitohi'. Also at Wakanui, mean falling number values were decreased ($p<0.01$) with increasing amounts of late N applied regardless of the early N status.

Table 4.7 Mean grain falling number values for hand and combine harvested crops of 'CRDW17' and 'Waitohi' at Darfield and Lincoln, and combine harvested values only at Wakanui with different N fertiliser treatments (Table 3.4).

Site							
			Darfield		Lincoln		Wakanui
Cultivar	Early N	Late N	Hand	Combine	Hand	Combine	Combine
'CRDW17'	0	0	205	173	188	109	103
	0	1	254	170	148	98	81
	0	2	305	172	156	109	75
	1	0	272	151	249	151	84
	1	1	270	130	212	108	76
	1	2	266	108	208	134	67
Mean	-	-	262	151	194	118	81
'Waitohi'	0	0	321	196	289	236	204
	0	1	329	234	289	245	146
	0	2	299	197	282	226	122
	1	0	309	116	300	229	99
	1	1	295	129	305	185	82
	1	2	288	145	224	167	77
Mean	-	-	307	170	282	215	122
SEM max	-	-	23.7	12.5	28.5	14.7	15.4
Significance							
* = 0.05			CV **	CV*	CV***	CV***	CV***
** = 0.01				E ***	CV*E*	CV*E***	E***
*** = 0.001				CV*E*			L**
							CV*E**

All subsequent grain testing was carried out on the hand harvested samples from Darfield and Lincoln and the header harvested samples from Wakanui.

4.3.2 Protein content

The minimum acceptable grain protein content standard for durum wheat is 11.5% in New Zealand. At all sites, each crop that had early N applied achieved at least this standard. However, there were some crops at each site that failed to attain this level. Specifically, at all sites the control treatment of no applied N produced the lowest grain protein content, with only some of the control plots at Wakanui producing above 11.5% protein content. The protein content was increased by 2.0-3.5% ($p<0.001$) with the single application of N at tillering for both cultivars at each site (Figure 4.4), and this application increased protein content of all crops to at least 12%.

For the crops that only received late N, grain protein content was increased ($p<0.01$) by about 1% for crops at each site for both cultivars. At Darfield, late N application caused a similar increase after early N application, but there was a smaller response for 'CRDW17' at Lincoln and Wakanui. This led to a cultivar effect at each site, with 'Waitohi' consistently attaining higher ($p<0.05$) grain protein content than 'CRDW17'.

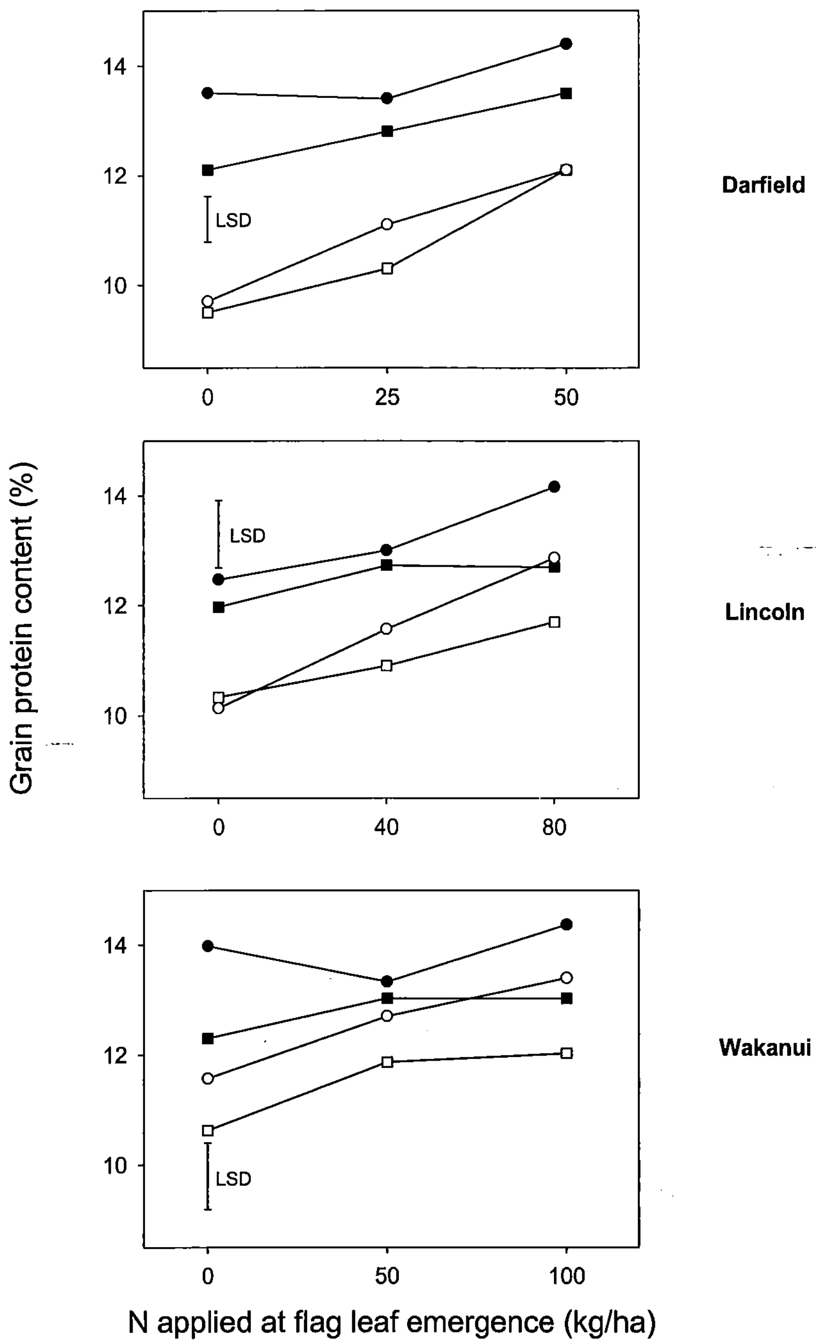

Figure 4.4 Relationships between mean grain protein content values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.4 Grain colour

4.4.1 b* value

At all sites grain yellowness as indicated by the b* value was highest for both cultivars where no early or late N had been applied (Figure 4.5). Grain b* values were decreased ($p<0.001$) by at least one unit with the application of only early N, while applying only late N decreased ($p<0.001$) it by 1 to 4 units at each site. The actual values attained were site specific and dependent on interactions.

At Darfield there was a three-way interaction ($p<0.05$) between cultivar and early and late N applications. Where no early N was applied, a late application of 25 kg N/ha caused a linear decline in b* values in both cultivars. However, increasing the late N application from 25 to 50 kg N/ha increased the b* value for 'CRDW17' from 24.7 to 25.3, but decreased 'Waitohi' from 25.3 to 24.0 (Figure 4.5). Furthermore, where early N had been applied, the late N did not significantly affect grain b* values for 'Waitohi' but led to a 0.5 unit decrease for 'CRDW17'.

At Lincoln there was an interaction ($p<0.001$) between early and late N applications. Where only late N was applied, a near-linear decrease of about 3 units occurred when up to 80 kg N/ha was applied (Figure 4.5). In contrast, the corresponding decrease was only 0.5 units when 80 kg/ha late N was applied following early N application. The cultivar main effect showed a higher ($p<0.05$) mean b* value for 'Waitohi' (24.4) than 'CRDW17' (23.8) over all treatments.

Results at Wakanui followed a similar pattern to those at Lincoln. However, greater variability meant that no differences were significant.

4.4.2 a* value

At all sites there was only a cultivar effect ($p<0.001$) for a* value readings. N had no effect on a* values. 'Waitohi' consistently had a mean a* value at least 0.5 units higher than 'CRDW17' (Figure 4.6), but the absolute values varied among sites.

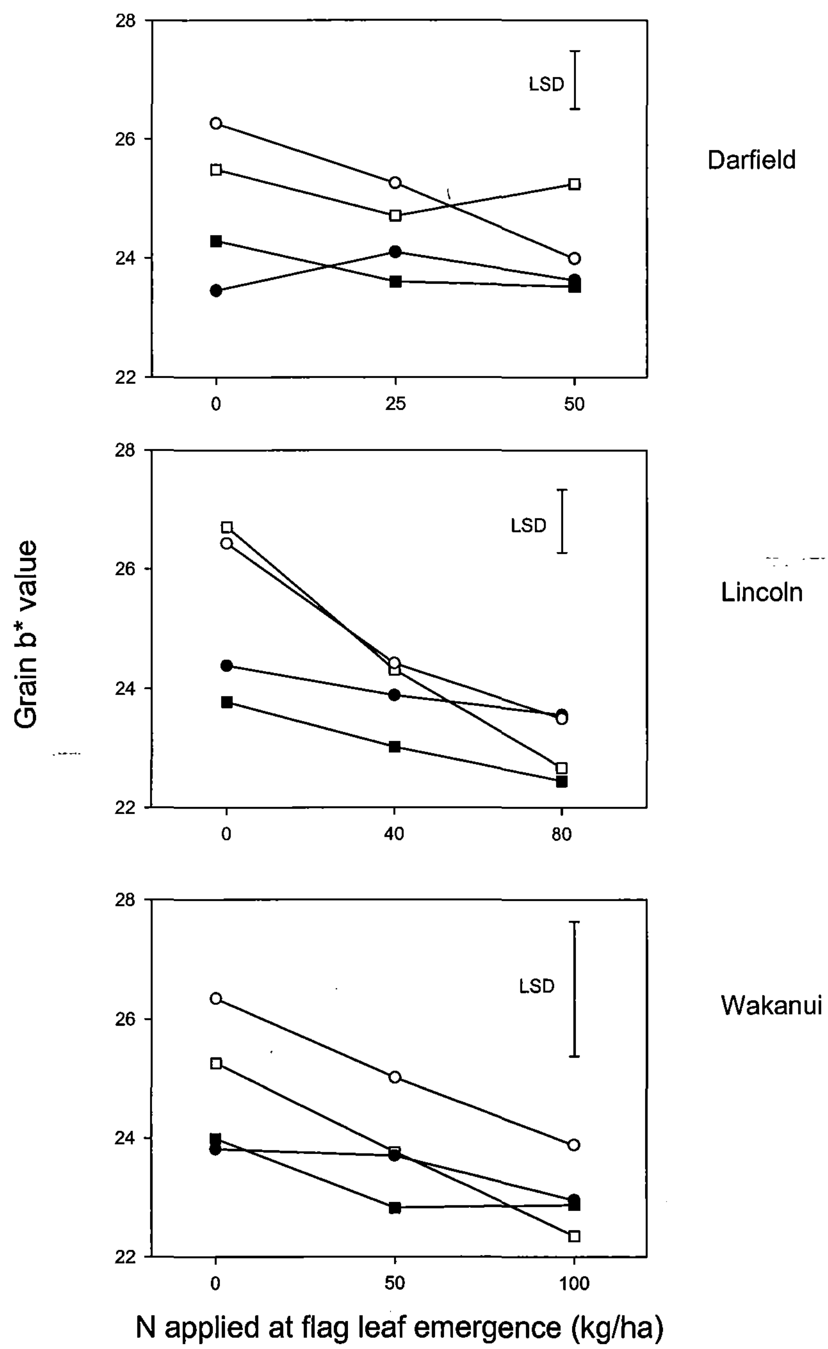

Figure 4.5 Relationships between mean grain b* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

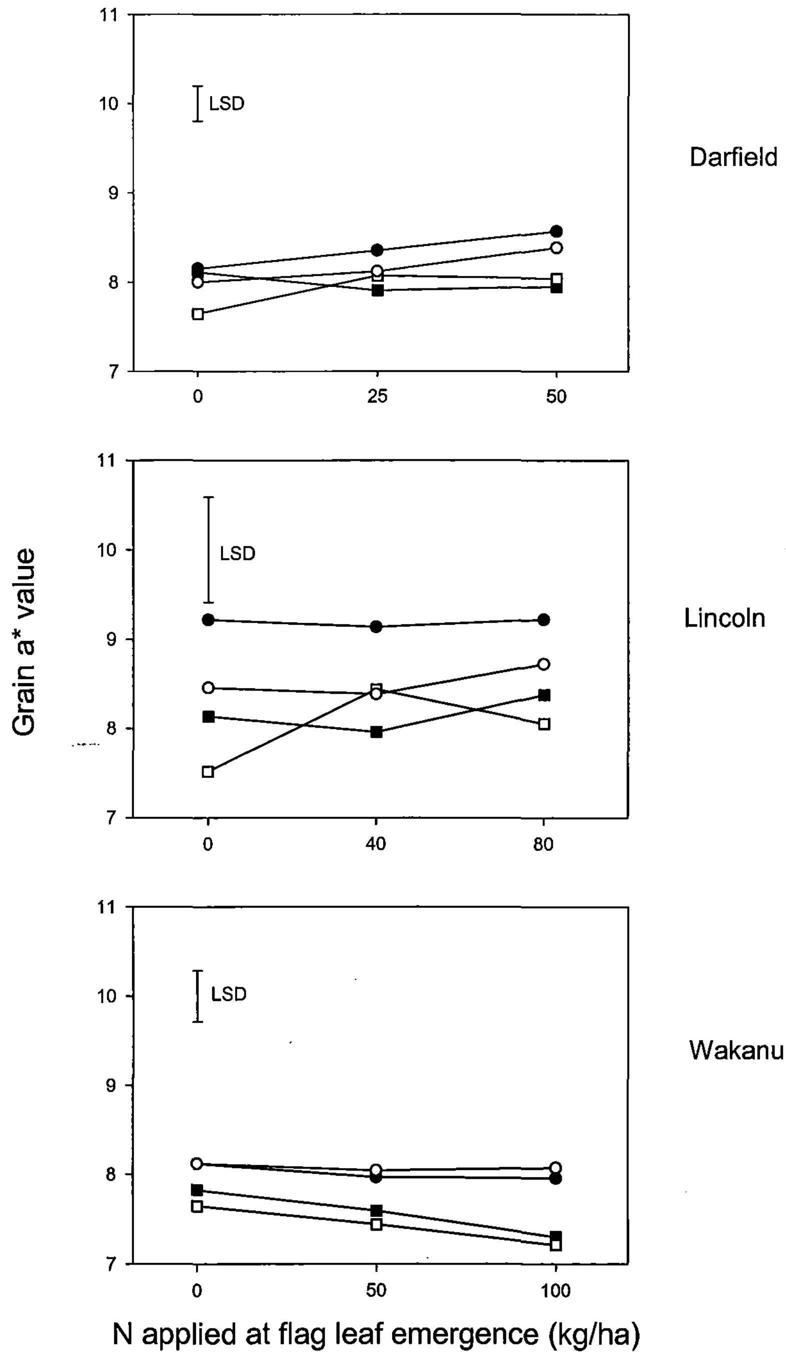

Figure 4.6 Relationships between mean grain a* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.4.3 Hue

At all sites, the highest hue angle value was achieved when no early or late N was applied for both cultivars (Figure 4.7).

At Darfield, there were two two-way interactions ($p<0.01$) for the early by late N and late N by cultivar effects. When no early N was applied, 25 kg N/ha applied at flag leaf emergence decreased grain hue values by about one unit (Figure 4.7). However, the decrease due to late N following early N was less for 'CRDW17' than 'Waitohi'.

At Lincoln mean hue angle was decreased ($p<0.001$) by early N alone and decreased ($p<0.001$) further when late N was applied (Figure 4.7). The cultivar main effect ($p<0.01$) showed a higher mean hue angle for 'CRDW17' (71.2) than 'Waitohi' (70.0).

Similarly, at Wakanui where only early N was applied, the mean hue angle decreased ($p<0.001$) with late N (Figure 4.7). There was a higher ($p<0.05$) mean for 'CRDW17' (72.3) than for 'Waitohi' (71.6).

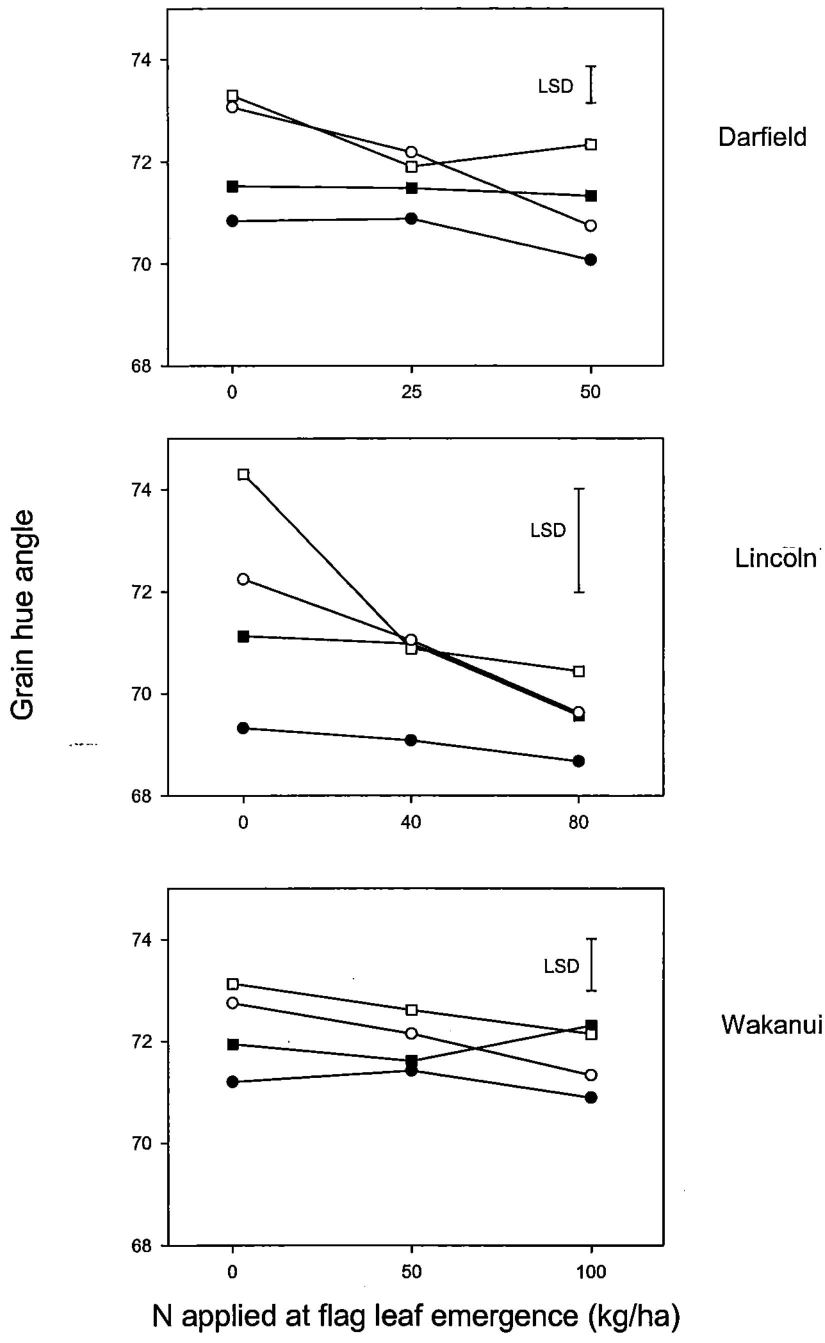

Figure 4.7 Relationships between mean grain hue angle values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.4.4 Chroma

At each site, the highest chroma value occurred for both cultivars when no N was applied (Figure 4.8). Application of only early N decreased ($p<0.05$) the mean chroma value by at least 1 unit at all sites.

At Darfield, there was a three-way interaction ($p<0.05$) with cultivar and N treatments. Where no early N was applied, 25 kg N/ha applied late only decreased grain chroma from 26.6 to 26.0 for 'CRDW17' but from 27.5 to 25.4 for 'Waitohi' (Figure 4.8). In addition, a sole application of 50 kg N/ha decreased grain chroma for 'Waitohi' to 25.4 and increased the mean for 'CRDW17' to 26.5. Where early N was applied the effect of late N application was minimal.

At Lincoln, there was an interaction ($p<0.01$) between the effects of early and late N. Late N application following early N application caused a decrease in grain chroma values (Figure 4.8). However, there was a sharper decrease when only late N was applied. In addition, the mean chroma values for 'Waitohi' (26.0) were higher ($p<0.01$) than for 'CRDW17' (25.2) over all N treatment combinations.

At Wakanui, the late N main effect decreased ($p<0.05$) grain chroma for both cultivars regardless of early N status. In addition, a single early N application also decreased ($p<0.05$) mean grain chroma values for both cultivars.

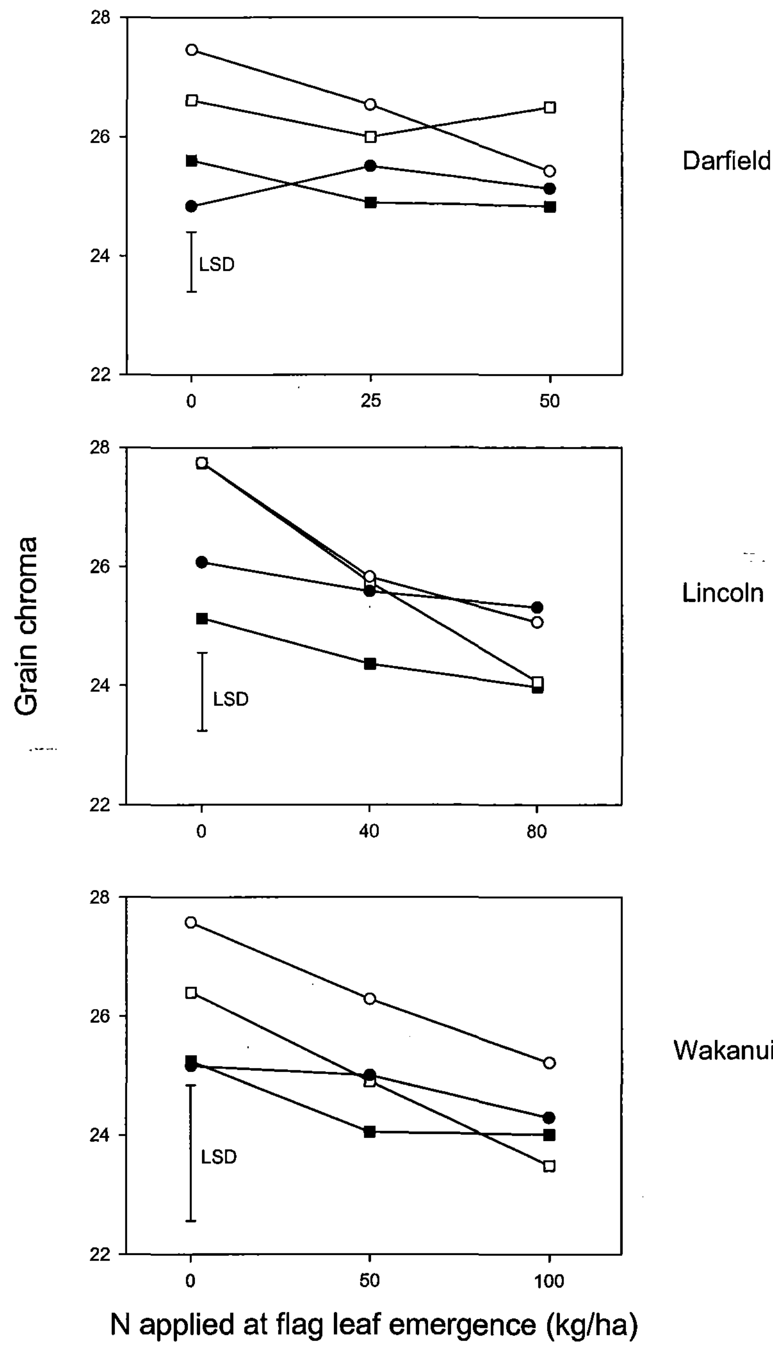

Figure 4.8 Relationships between mean grain chroma values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.4.5 L* value

The highest L* value at each site occurred when no N was applied to either cultivar (Figure 4.9). The application of N at tillering decreased ($p<0.05$) grain L* values by 1.5 to 3 units for both cultivars at all sites.

At Darfield, N applied only at flag leaf emergence decreased ($p<0.001$) the grain L* value by 2 to 4 units for both cultivars (Figure 4.9), except for one 'CRDW17' value.

At Lincoln, there was an interaction ($p<0.01$) between the effects of early and late N applications. An application of 40 kg/ha of late N decreased grain L* values by 1- 3 units for both cultivars (Figure 4.9), but there was no further decrease from additional N or from late N when early N had been applied.

The early N main effect ($p<0.05$) was the only significant result at Wakanui.

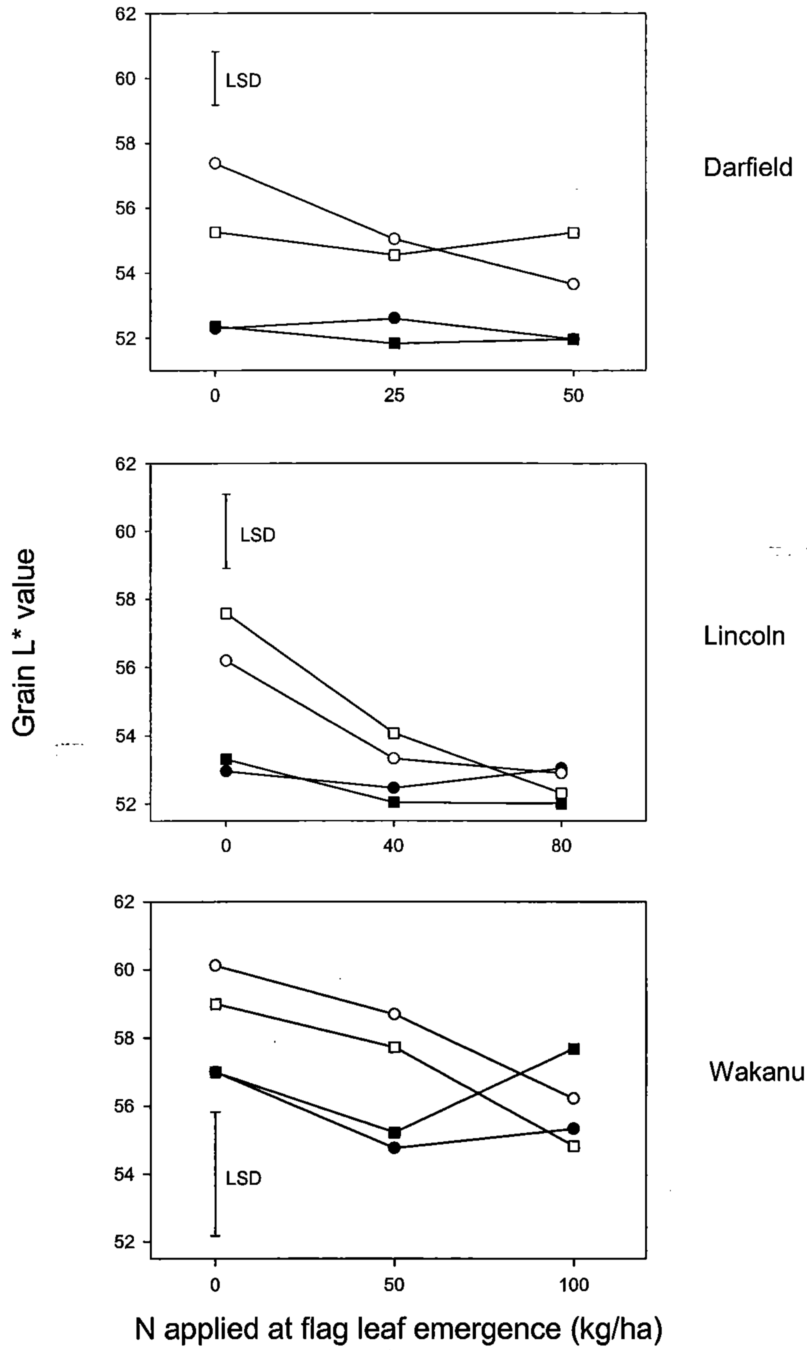

Figure 4.9 Relationships between mean grain L* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.5 Flour Quality

Flour analysis was carried out on the hand harvested samples from Darfield and Lincoln. Emphasis was placed on results from these samples, as they were more indicative of the kind of grain and flour accepted and used in industry situations. In addition, results from the combine harvested samples from Wakanui are presented for completeness because no hand harvested samples were available from this site.

4.5.1 Falling number

Flour falling number at Darfield and Lincoln was affected by the interacting ($p<0.05$) effects of cultivar and early N application. At Darfield, early N application increased the mean falling number for 'CRDW17' from 309 to 317 s but it decreased the mean from 340 to 314 s for 'Waitohi'. Similarly at Lincoln, early N increased the mean falling number for 'CRDW17' from 209 to 234 s, but decreased it from 316 to 276 s for 'Waitohi' (Table 4.8). In addition, at Wakanui the mean falling number was decreased ($p<0.001$) by about 50 s with a sole application of early N, and the mean for 'Waitohi' was higher than the 'CRDW17' value.

Table 4.8 Mean flour falling number values (seconds) for two cultivars of durum wheat ('CRDW17' and 'Waitohi') grown at three locations (Darfield, Lincoln and Wakanui) under different N fertiliser treatments (Table 3.4). Data for Darfield and Lincoln is from hand harvested samples taken prior to 14 mm of rainfall and for post-rain combine harvested samples at Wakanui. Standard error values are from the three-way interaction.

Treatment			Site		
Cultivar	**Early N**	**Late N**	**Darfield**	**Lincoln**	**Wakanui**
'CRDW17'	0	0	299	200	169
	0	1	307	214	142
	0	2	322	213	142
	1	0	335	255	115
	1	1	306	222	118
	1	2	311	225	137
Mean	-	-	313	222	137
'Waitohi'	0	0	345	329	181
	0	1	347	323	222
	0	2	327	295	203
	1	0	304	292	132
	1	1	312	280	151
	1	2	326	254	140
Mean	-	-	327	296	172
SEM max	-	-	10.6	12.7	16.7
Significance * = 0.05 ** = 0.01 *** = 0.001			CV* CV* E**	CV*** CV*E***	CV** E***

4.5.2 Protein content

Predictably, the flour protein content of all samples was strongly correlated (r< 0.80) with corresponding grain protein values (Figure 4.10). However, the flour values were consistently lower than the grain ones because of the removal of bran and embryo.

At all sites, the highest flour protein content values were achieved by 'Waitohi' crops where early N was applied (Figure 4.11). 'CRDW17' crops without early N application produced the lowest flour protein content values at Lincoln and Wakanui.

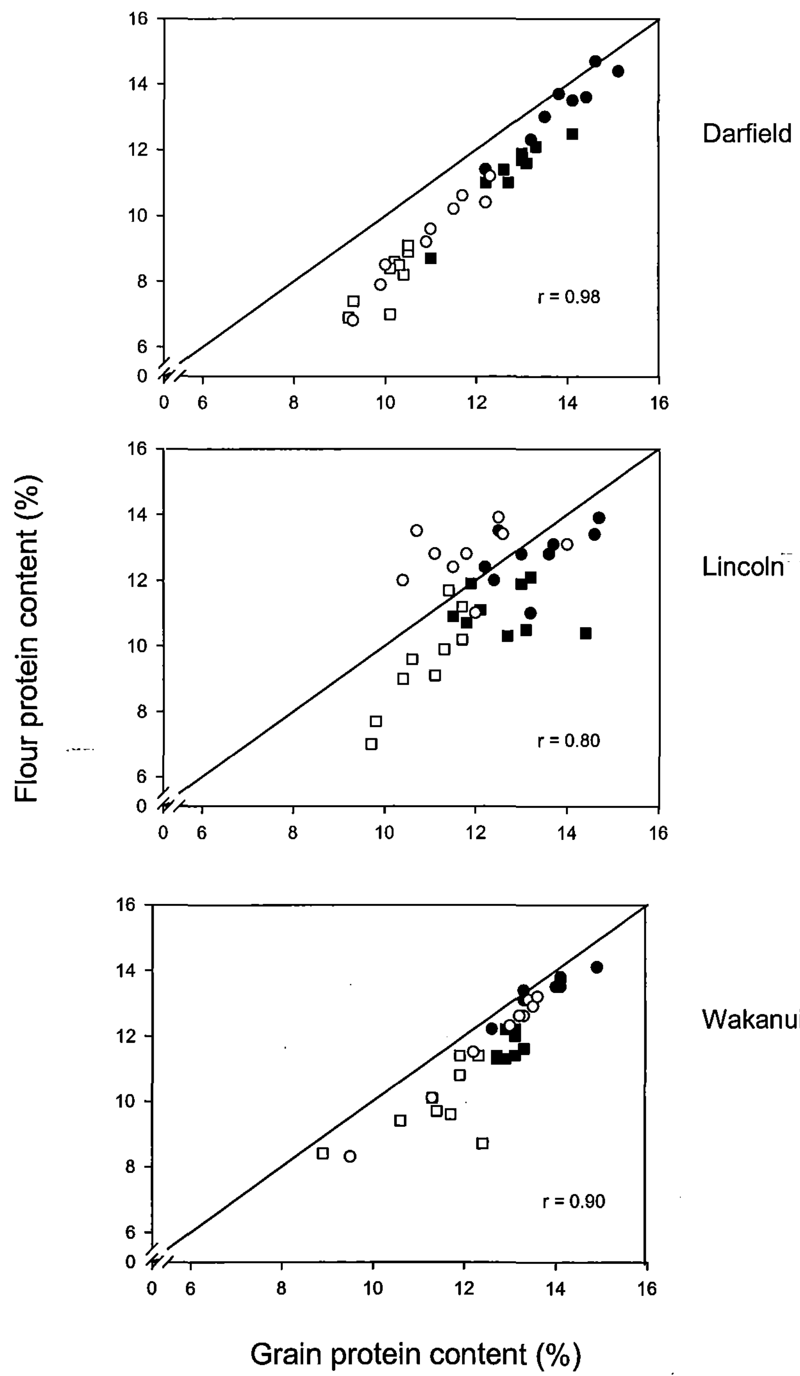

Figure 4.10 Relationships between grain and flour protein content values for durum wheat ('CRDW17' (■) and 'Waitohi' (●)) grown at three sites (Darfield, Lincoln and Wakanui). Early N was applied at tillering (closed symbols) or not at all (open symbols).

There were no interactions at Darfield, but early N application increased ($p<0.001$) mean flour protein content by 3.6% and, in most cases late N produced a further increase (Figure 4.11). In addition, the mean flour protein content was 1.5% higher ($p<0.001$) for 'Waitohi' than for 'CRDW17'.

At Lincoln, the flour protein content was affected by the interaction ($p<0.001$) between the effects of early and late N. When no early N was applied, 80 kg N/ha applied late increased the mean flour protein content by 3% for 'CRDW17' and by 4.5% for 'Waitohi' (Figure 4.11). However, when early N was applied, the increase was only 0.5 to 1.0%. Again, the protein content for 'Waitohi' was always at least 0.5% higher ($p<0.05$) than for 'CRDW17' regardless of the N treatment.

At Wakanui, only the cultivar effect was significant ($p<0.001$) with a mean of 12.7% for 'Waitohi' and 10.7% for 'CRDW17' (Figure 4.11).

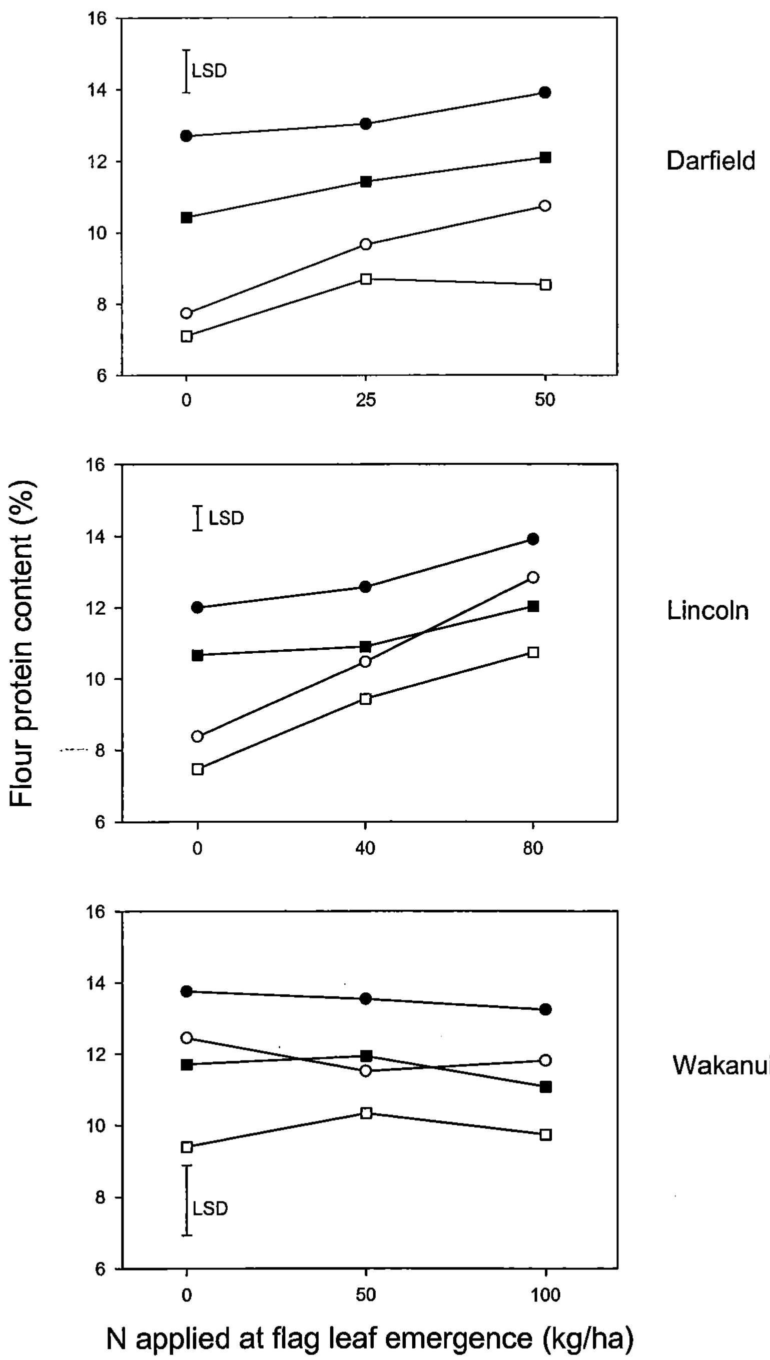

Figure 4.11 Relationships between mean flour protein content values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.5.3 Rheological testing

Due to the severity of sprout damage, the results from Wakanui are not presented here. However, they are presented in the Appendix 1 for completeness.

4.5.3.1 Water absorption, stability time and development time

Results of rheological testing were inconsistent between sites and across treatments (Table 4.9). For example, water absorption was lowest for the control treatments at both Darfield and Lincoln, but the effects of early and late N applications differed.

At Darfield, there was no consistent response of water absorption to N treatment with an early by late N interaction and a cultivar by early N interaction. At Lincoln, there were no interactions between factors but early ($p<0.01$) and late N ($p<0.01$) both increased water absorption.

Results for stability time were also inconsistent, ranging from 1.1 to 6.8 minutes at Darfield and 2.3 to 7.6 minutes at Lincoln (Table 4.9). The stability time was lowest for the control treatment at Darfield but not at Lincoln. In addition, there was a cultivar effect ($p<0.01$) at Lincoln, with 'Waitohi' (6.1 minutes) having a higher mean stability time than 'CRDW17' (3.3 minutes). There was an interaction ($p<0.05$) between the effects of cultivar and late N application at Darfield. When only 50 kg N/ha was applied late to 'CRDW17' the stability time increased from 1.1 to 1.3 minutes but it increased from 1.7 to 6.8 minutes for 'Waitohi'.

Mean development time was higher at Lincoln (3.6 minutes) than at Darfield (2.3 minutes). At both locations the control had the lowest development time with an increase ($p<0.05$) caused by early N applications. However at Lincoln, the effect of late N depended ($p<0.001$) on the early N status. Late N only increased the development time when no early N was applied. Also at Lincoln, the cultivar effect ($p<0.001$) showed a higher mean development time for 'Waitohi' (4.2 minutes) than for 'CRDW17' (3.0 minutes)

Table 4.9 Mean water absorption, stability time and development time for durum wheat cultivars ('CRDW17' and 'Waitohi') grown at Darfield and Lincoln sites with different N fertiliser treatments (Table 3.4).

Darfield

Cultivar	**Early N (kg/ha)**	**Late N (kg/ha)**	**Water absorption (%)**	**Stability time (minutes)**	**Development time (minutes)**
'CRDW17'	0	0	65.8	1.1	1.4
	0	25	67.7	1.4	1.9
	0	50	66.8	1.3	2.0
	150	0	69.2	4.2	3.0
	150	25	68.1	5.1	2.8
	150	50	71.2	3.2	2.8
Mean	-	-	68.1	2.7	2.3
'Waitohi'	0	0	66.1	1.7	1.7
	0	25	69.5	4.2	2.1
	0	50	70.2	6.8	2.6
	150	0	69.4	6.4	3.3
	150	25	67.1	5.7	2.5
	150	50	69.7	5.9	2.1
Mean	-	-	68.7	5.1	2.3
SEmax	-	-	0.88	0.61	0.54
Significance * = 0.05 ** = 0.01 *** = 0.001			Early N* Late N* CV * Early N* Early N * Late N*	Early N*** CV*** CV * Late N*	Early N*

Lincoln

Cultivar	**Early N (kg/ha)**	**Late N (kg/ha)**	**Water absorption (%)**	**Stability time (minutes)**	**Development time (minutes)**
'CRDW17'	0	0	61.8	3.5	1.8
	0	40	66.3	2.3	2.4
	0	80	67.7	3.6	3.1
	175	0	66.2	3.6	3.5
	175	40	68.1	3.0	3.4
	175	80	68.2	3.5	3.7
Mean	-	-	66.4	3.3	3.0
'Waitohi'	0	0	63.0	4.0	2.0
	0	40	66.1	4.0	2.2
	0	80	67.0	7.6	5.1
	175	0	67.4	7.3	6.4
	175	40	67.7	7.6	4.5
	175	80	68.4	6.2	4.9
Mean	-	-	66.6	6.1	4.2
SEmax			1.12	1.20	0.46
Significance * = 0.05 ** = 0.01 *** = 0.001			Early N** Late N**	CV**	Early N*** Late N* CV*** Early N* Late N**

4.5.4 Flour colour

4.5.4.1 b value*

At Darfield the flour b* values were affected ($p<0.05$) by cultivar and the interacting effects of early and late N applications. Where only late N was applied there was a positive linear increase for 'Waitohi' but a decrease for 'CRDW17' when 50 kg N/ha was applied at flag leaf emergence (Figure 4.12). Application of late N following early N did not affect flour b* value for 'CRDW17' but it decreased the value for 'Waitohi' when 50 kg N/ha was applied.

At Lincoln, the interacting effects of early and late N ($p<0.001$) indicated that a sole late application of N increased the flour b* values for both cultivars (Figure 4.12), whereas late N applied following 175 kg N/ha at tillering did not significantly affect flour b* values.

At Wakanui, there was only an early N main effect ($p<0.05$) with an increase in flour b* values after 150 kg N/ha was applied alone.

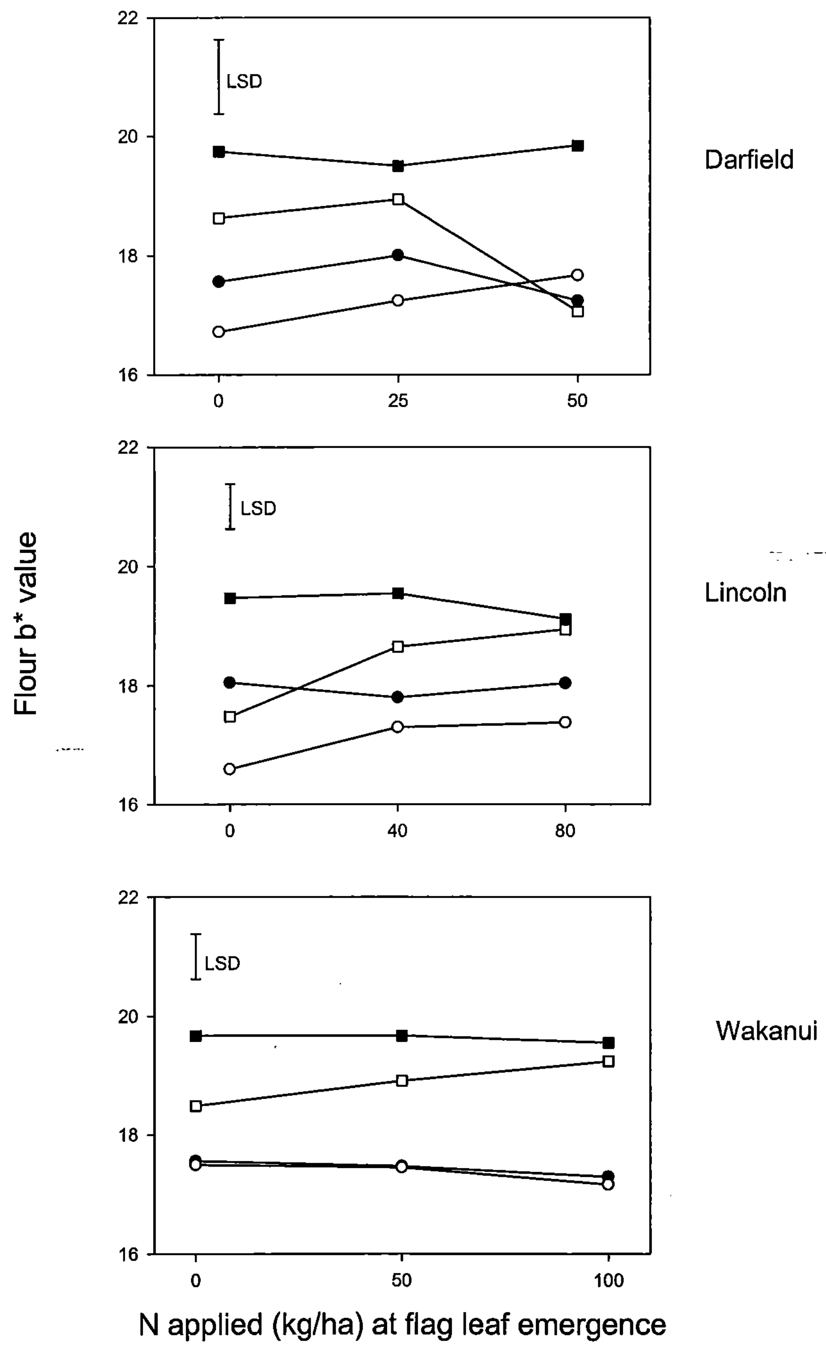

Figure 4.12 Relationships between mean flour b* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

There was a negative relationship between grain and flour b* values at all locations. The correlation coefficients ranged from -0.25 to -0.47, illustrating that the relationship between the two variables was not strong. The highest flour b* value was achieved consistently by a 'CRDW17' crop that had early N applied (Figure 4.13), with 'Waitohi' having the lowest value at all sites.

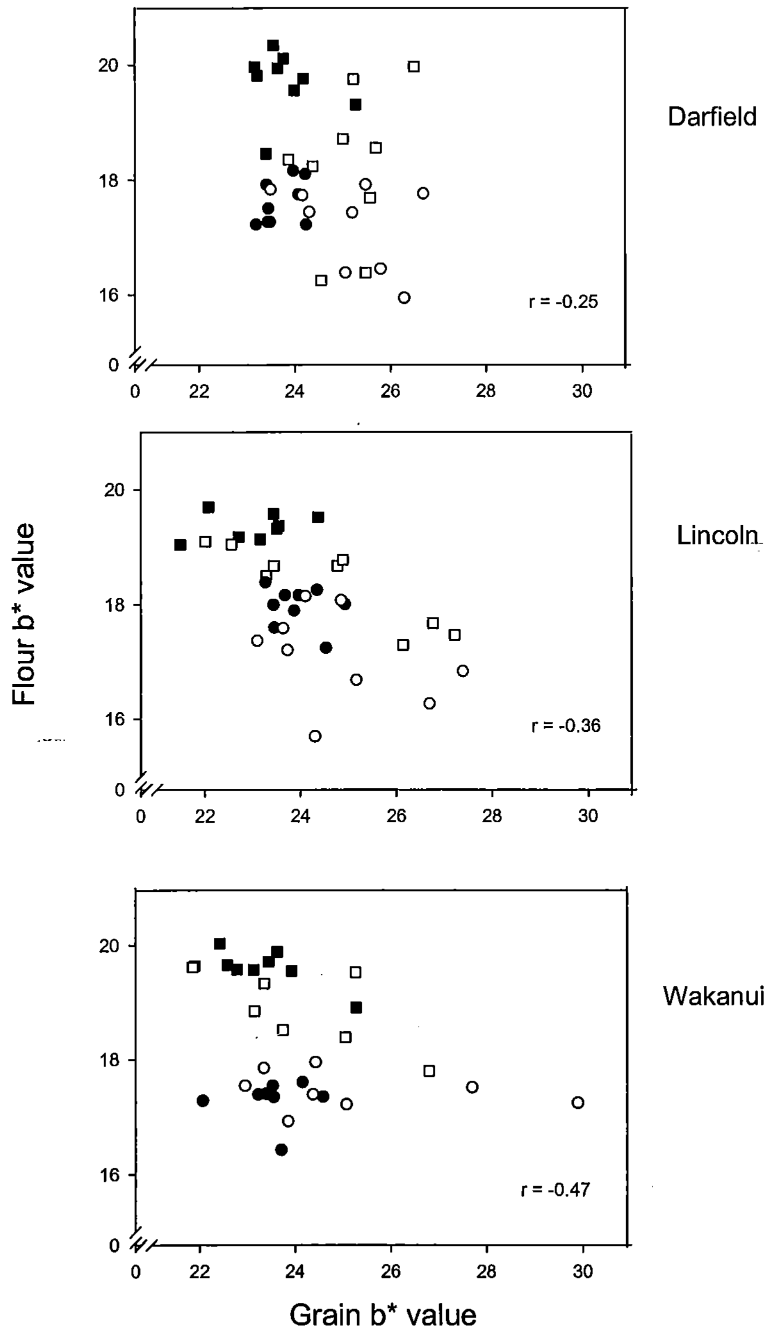

Figure 4.13 Relationship between grain and flour b* values for two cultivars of durum wheat ('CRDW17' and 'Waitohi') grown at three sites (Darfield, Lincoln and Wakanui).

4.5.4.2 *a* value*

In most cases at Darfield and Wakanui, the flour a* value increased when early N was applied ($p<0.05$), but there was little additional effect of late N (Figure 4.14). In contrast, at Lincoln only late N increased ($p<0.001$) flour a* values. Also a* values at Darfield and Lincoln were higher ($p<0.01$) for 'Waitohi' than for 'CRDW17' regardless of treatment.

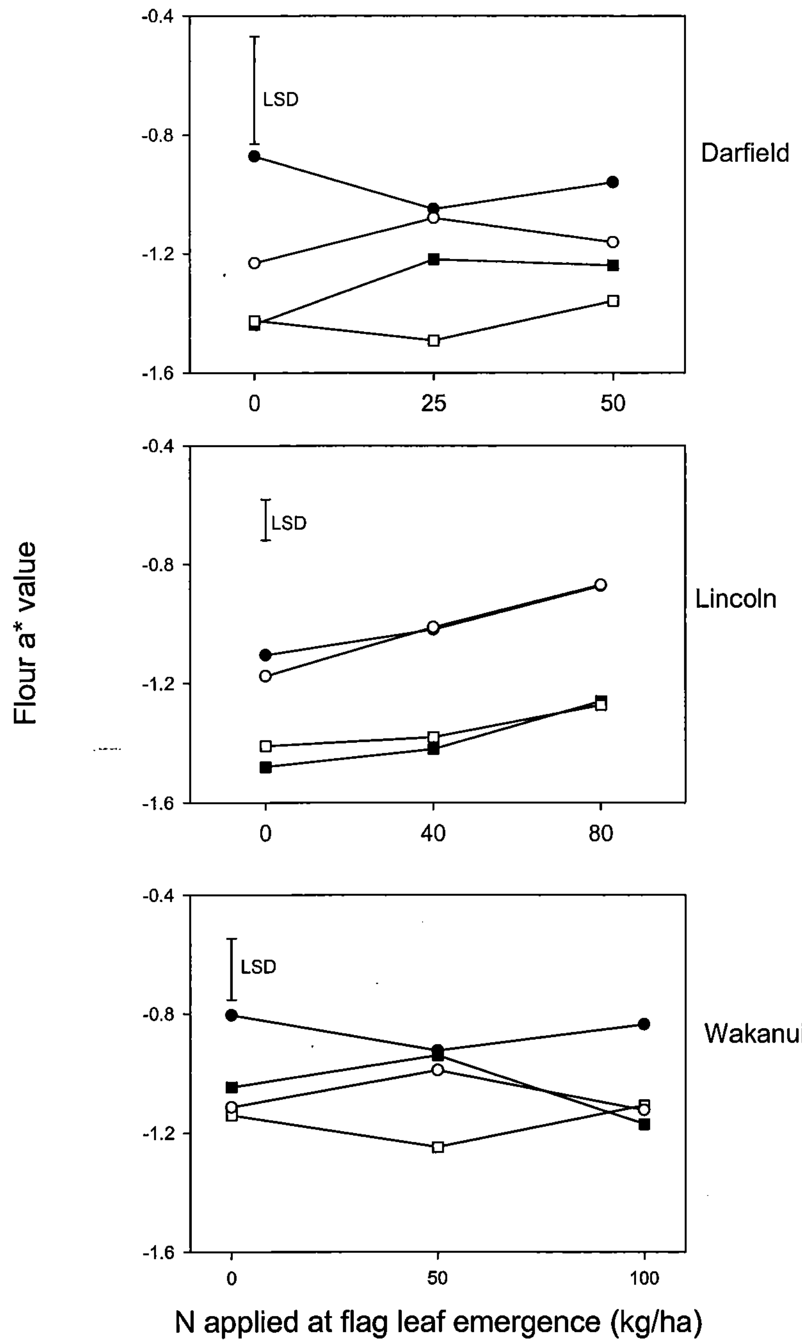

Figure 4.14 Relationships between mean flour a* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

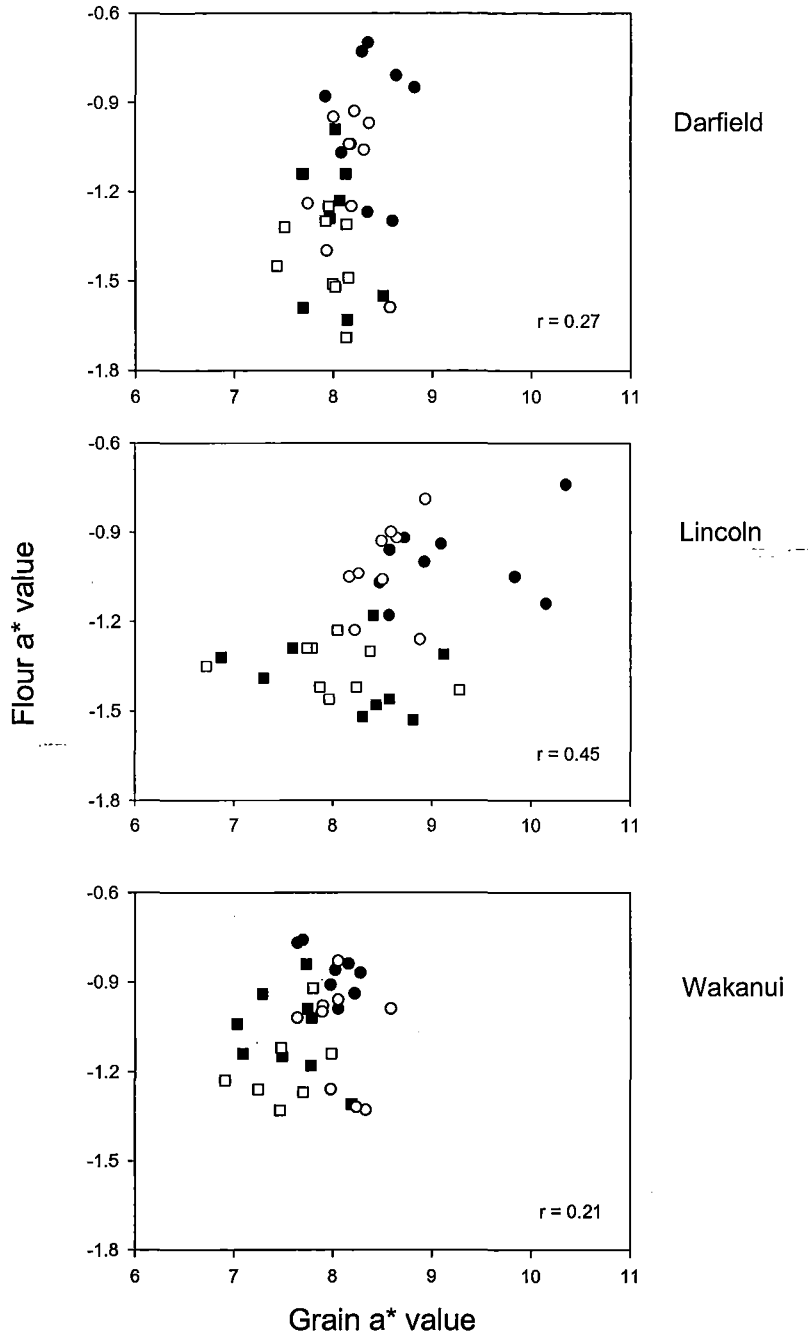

Figure 4.15 Relationship between grain and flour a* values durum wheat ('CRDW17' (■) and 'Waitohi' (●)) grown at three sites (Darfield, Lincoln and Wakanui). Early N was applied at tillering (closed symbols) or not at all (open symbols).

There was only a weak relationship between grain and flour a* values regardless of treatment with correlation coefficients ranging from 0.21 to 0.45. There was no consistent effect of cultivar or early N treatment.

4.5.4.3 Hue angle

Hue angle value, the combination of a* and b* values, was decreased by early N application ($p<0.05$). The magnitude differed among sites (Figure 4.16) with larger decreases at Darfield and Lincoln than at Wakanui. 'CRDW17' had a higher ($p<0.05$) mean hue angle than 'Waitohi' at both Darfield and Lincoln. At Lincoln, late N application caused a linear decline ($p<0.001$) in mean hue angle for both cultivars (Figure 4.16) regardless of early N status.

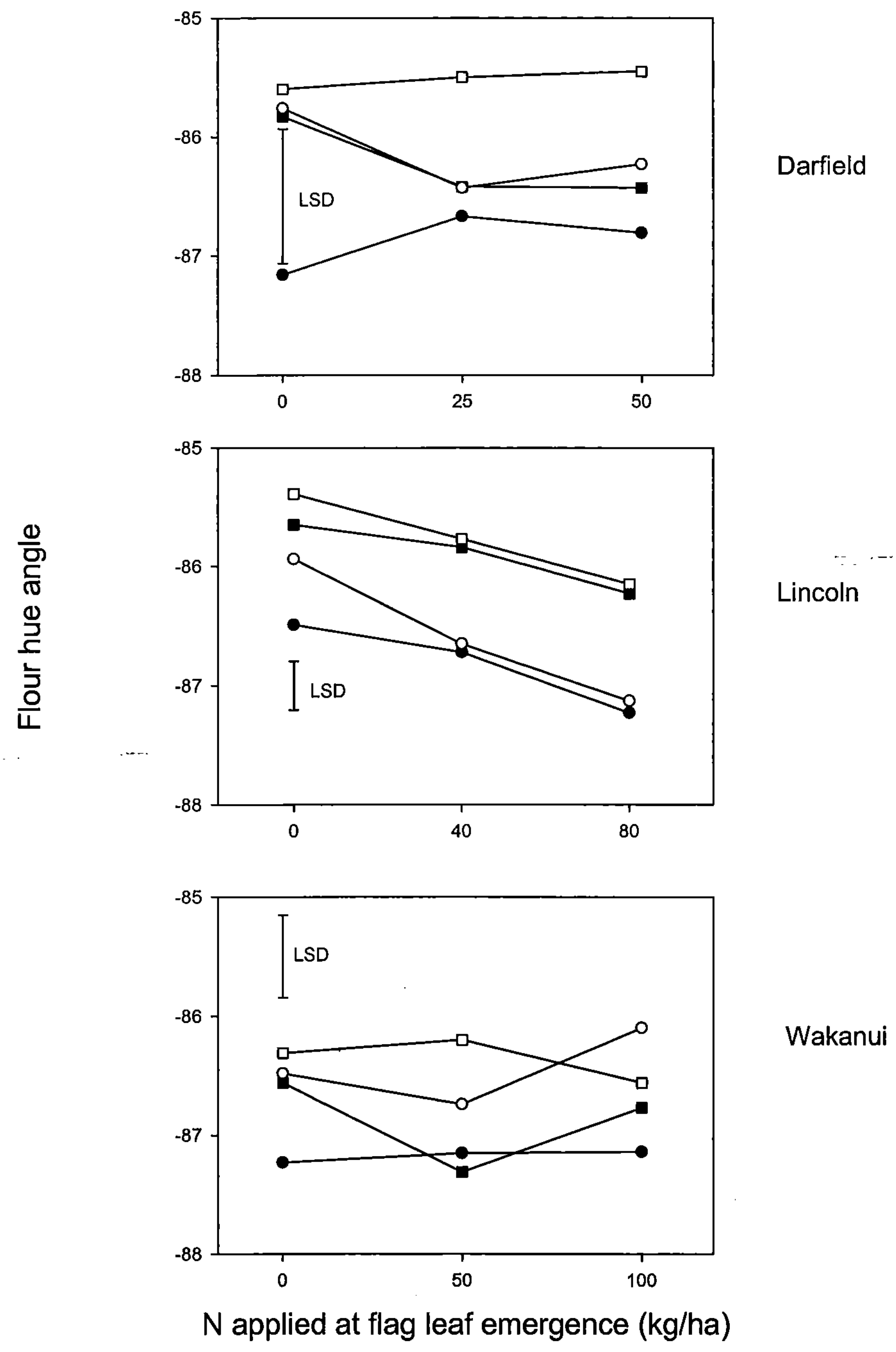

Figure 4.16 Relationships between mean flour hue angle values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.5.4.4 Chroma

Flour chroma differed between cultivars. It was higher ($p<0.001$) for 'CRDW17' than for 'Waitohi' at all sites (Figure 4.17). In addition, at Lincoln when N was applied at tillering only, flour chroma values increased ($p<0.001$) by at least 1 unit for both cultivars. Similarly, at Wakanui the sole application of early N increased the mean flour chroma values for 'CRDW17' but not for 'Waitohi' ($p<0.05$).

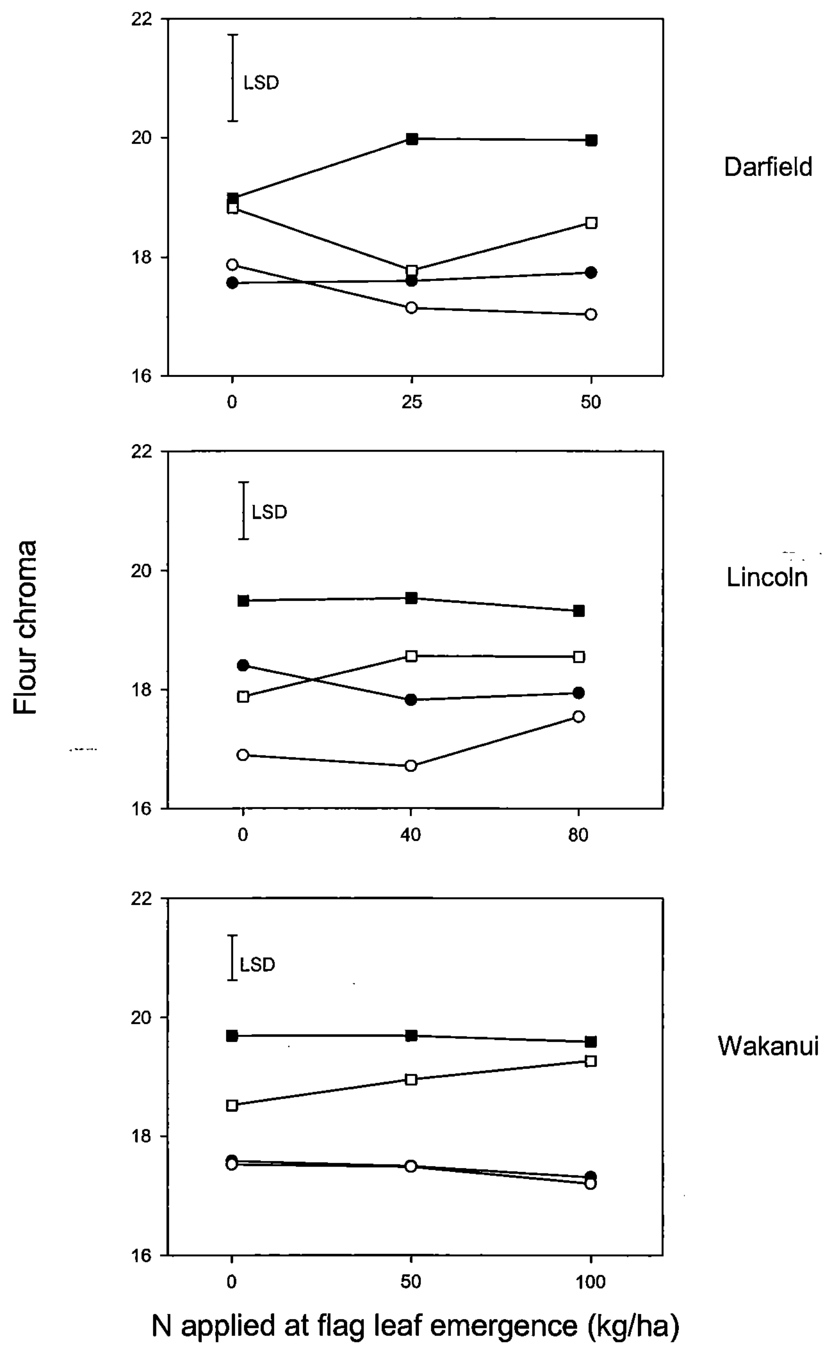

Figure 4.17 Relationships between mean flour chroma values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

4.5.4.5 L* value

The highest flour L* values were achieved where no early N was applied for both cultivars at all sites. At all sites the flour L* value was decreased ($p<0.001$) by early N application. Furthermore, at Lincoln there was an interaction ($p<0.001$) between the effects of early and late N applications. Where no early N was applied, 40 kg N/ha late decreased the mean flour L* values from 88.9 to 88.0 (Figure 4.18). However, where 40 kg N/ha late was applied following 175 kg N/ha at tillering the decrease was insignificant. There was a significant ($p<0.05$) difference between cultivars at Lincoln with mean L* values of 88.1 and 87.8 for 'CRDW17' and 'Waitohi' respectively. The same result occurred at Wakanui, where the mean for 'CRDW17' (87.6) was higher ($p<0.01$) than 'Waitohi' (87.1).

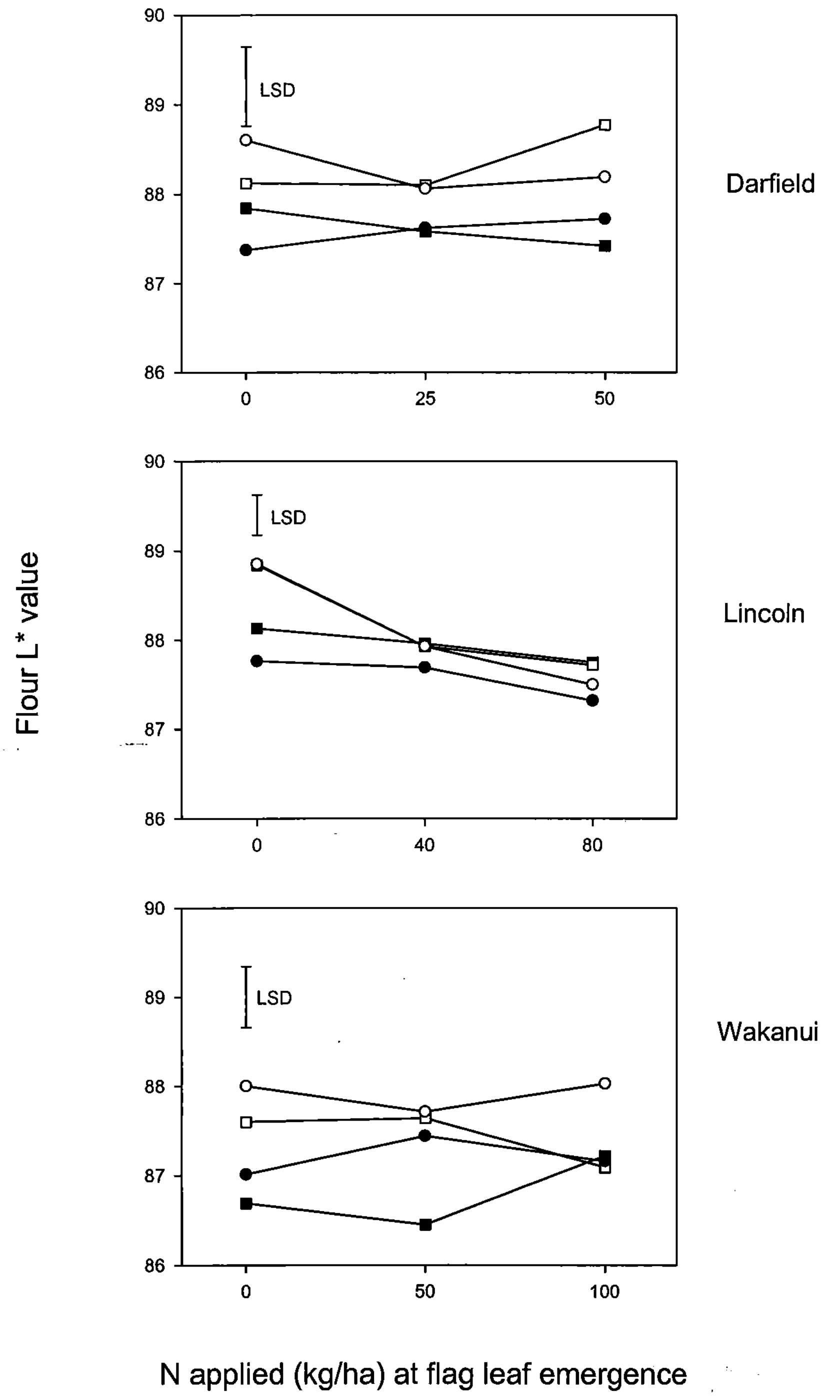

Figure 4.18 Relationships between mean flour L* values for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied (open symbols) or had been applied at 150 kg/ha (Darfield), 175 kg/ha (Lincoln) or 150 kg/ha (Wakanui). LSD represents error for the three-way interaction.

For the relationship between grain L* and flour L* values the correlation coefficients ranged from 0.50 to 0.68 (Figure 4.19). At each site, the highest grain and flour L* values were achieved by crops that had not received early N. There were no cultivar differences observed at any of the sites.

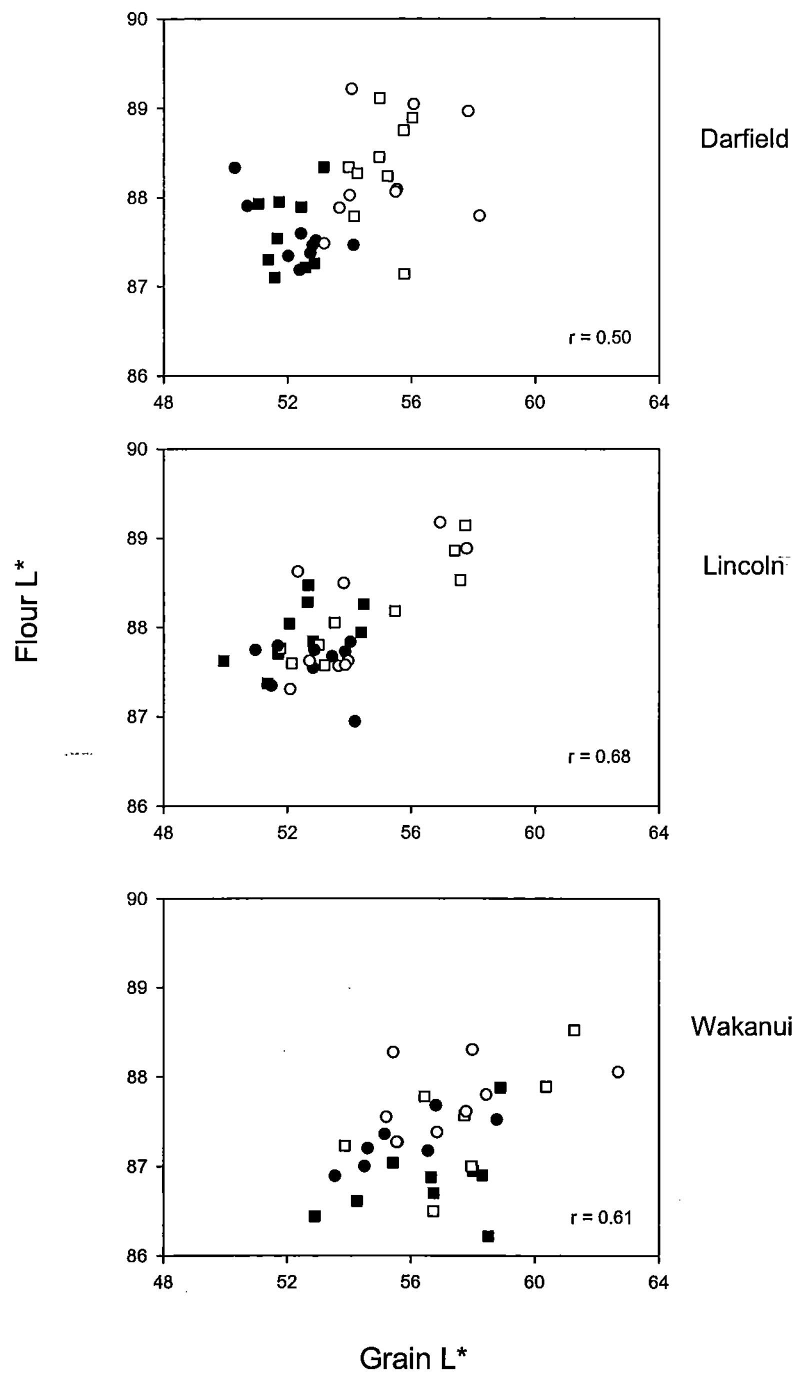

Figure 4.19 Relationship between grain and flour L* values for durum wheat ('CRDW17' (■) and 'Waitohi' (●) grown at three sites (Darfield, Lincoln and Wakanui). Early N was applied at tillering (closed symbols) or not at all (open symbols).

4.5.5 Flour carotenoid content

Flour carotenoid content was determined in combine harvested samples from Darfield and Lincoln and these were later extruded into pasta. Pasta was not extruded from Wakanui samples due to the severity of sprout damage at this site.

At both Lincoln and Darfield, 'CRDW17' had a higher ($p<0.05$) carotenoid content than 'Waitohi' (Figure 4.20) regardless of early N status. At Darfield the mean pigment content for 'CRDW17' was 0.28 mg/20 g flour compared with 0.21 mg/20 g flour for 'Waitohi'. Similarly at Lincoln, 'CRDW17' had a mean carotenoid content of 0.24 mg/20 g flour compared with 'Waitohi' at 0.18 mg/20 g flour. At Darfield, the lowest carotenoid content for both cultivars was in the control treatment. Early N application did not affect the carotenoid content for either cultivar at either site. Similarly, late N application did not significantly alter the carotenoid content for either cultivar except when only 50 kg N/ha was applied late to 'CRDW17' at Darfield. This caused a large unexplained increase in carotenoid content (Figure 4.20).

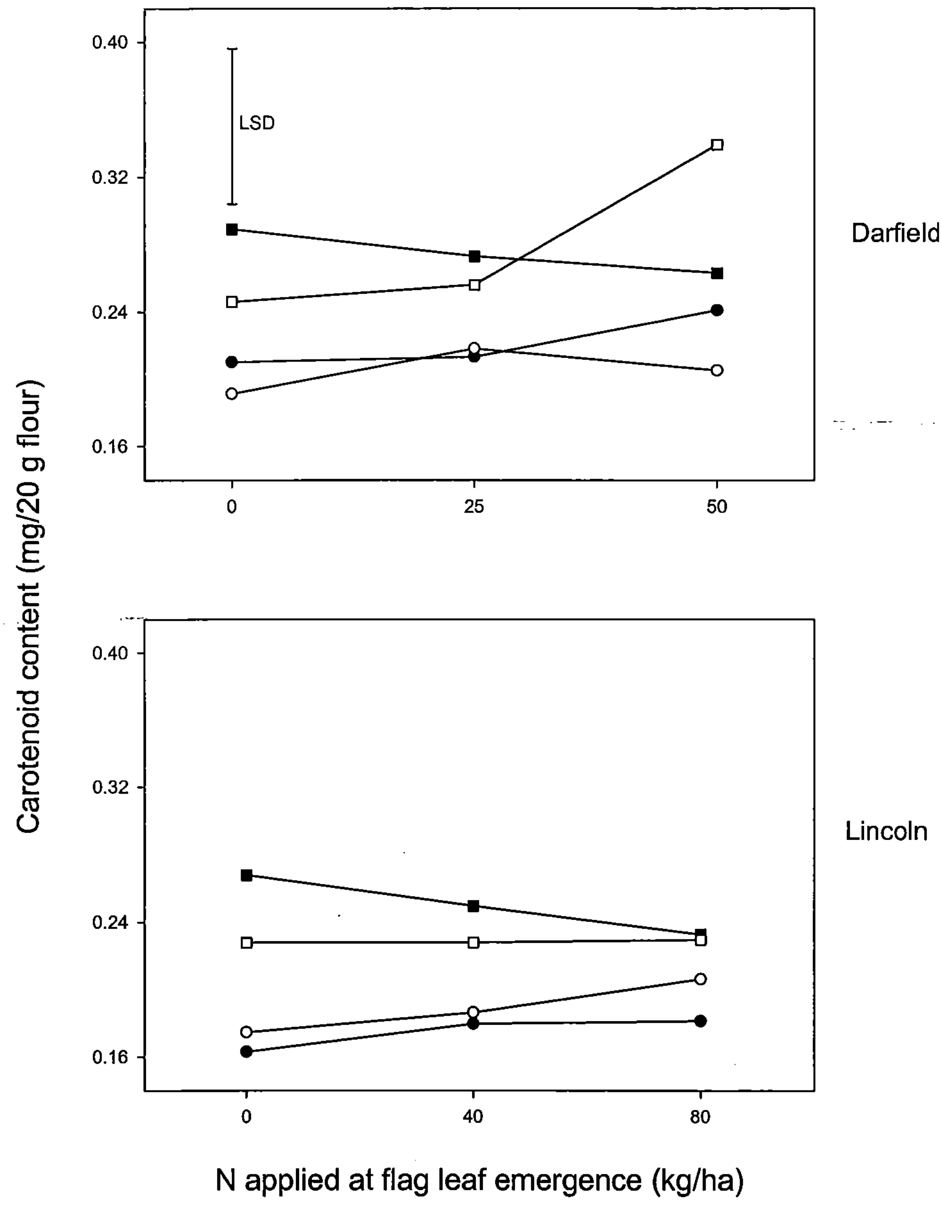

Figure 4.20 Relationship between flour carotenoid pigment values from Darfield and Lincoln for durum wheat ('CRDW17' ( ) and 'Waitohi' (●)) and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied at all (open symbols) or had been applied at 150 kg/ha (Darfield) or 175 kg N/ha (Lincoln). LSD represents error for the three-way interaction.

There was a negative correlation between flour carotenoid content and flour L* (r = -0.10) and flour a* (r = -0.39) (Figure 4.21). For the relationship with flour L* values, there were no consistent cultivar or N treatment affects. However, for the flour a* values the highest carotenoid content was again achieved by 'CRDW17' crops without early N applied, but the range in flour a* values was small.

There was a positive correlation between flour b* values (Figure 4.21) and flour carotenoid content (r = 0.58). In general, 'CRDW17' had higher pigment content values than 'Waitohi' (Figure 4.21) which was in accordance with the higher flour b* values for 'CRDW17'.

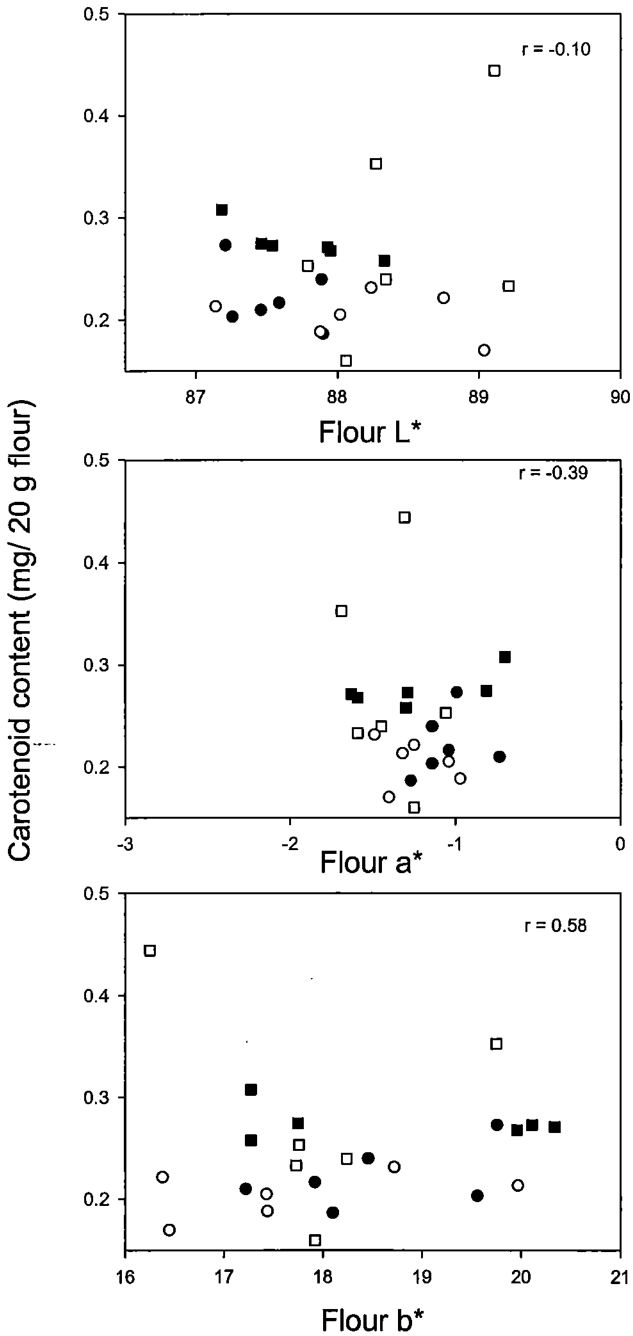

Figure 4.21 Relationships between carotenoid pigment content and flour L* a* and b* values for durum wheat ('CRDW17' ( ) and 'Waitohi' (●)) grown at Darfield and Lincoln. Early N was applied at tillering (closed symbols) or not at all (open symbols).

4.6 Pasta quality

Flour from two replicates at Darfield and one replicate at Lincoln was extruded to pasta. The number of samples able to be processed was limited by the fact that the time required for milling and extrusion was over five hours per sample. Samples from Wakanui were not extruded due to their severe sprout damage. Statistical analysis was carried out on results from the Darfield samples but this was not possible for the single replicate from Lincoln. However, values from Lincoln are reported for comparison.

4.6.1 Pasta colour

4.6.1.1 b value*

There were no significant ($p < 0.005$) effects of any of the treatments on pasta b* values at Darfield (Figure 4.22). However, there was an indication ($p<0.1$) that 'CRDW17' (27.1) had a higher mean pasta b* value than 'Waitohi' (24.1). Simlarly at Lincoln, 'CRDW17' had a mean pasta b* value of 22.4 compared to 20.3 for 'Waitohi' (Figure 4.23).

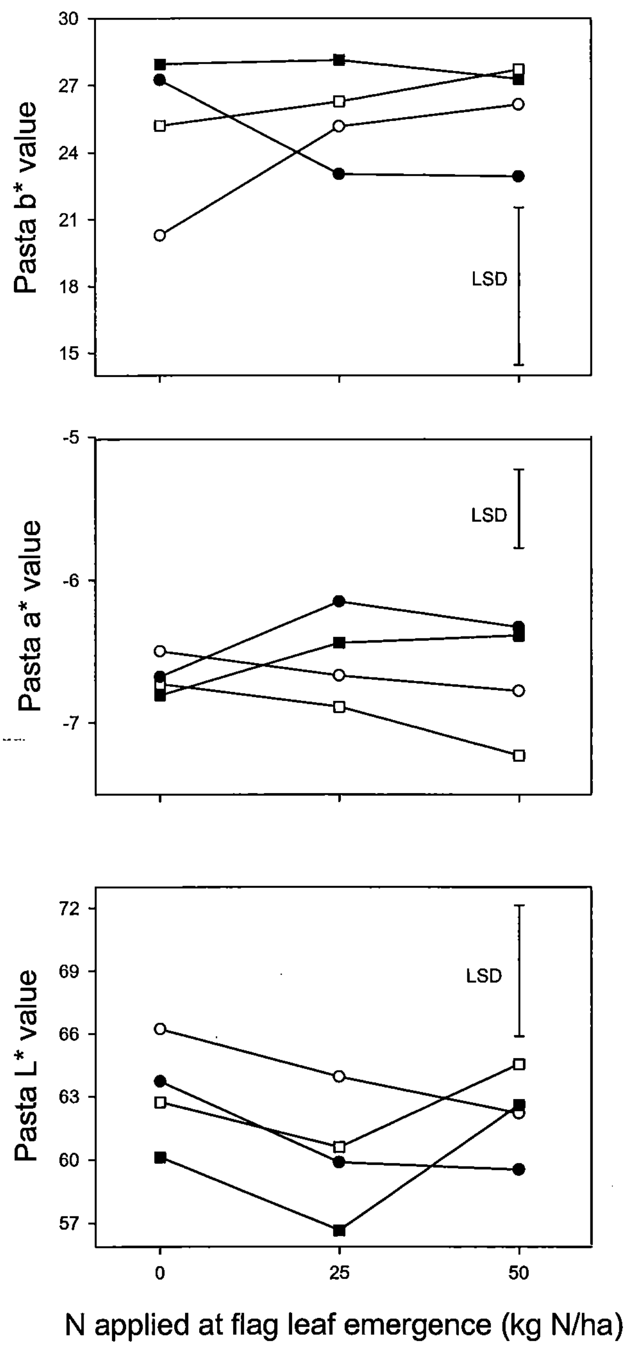

Figure 4.22 Relationships between mean pasta L* a* b* values at Darfield for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either been not been applied at all (open symbols) or had been applied at 150 kg/ha. LSD represents maximum error for the three-way interaction.

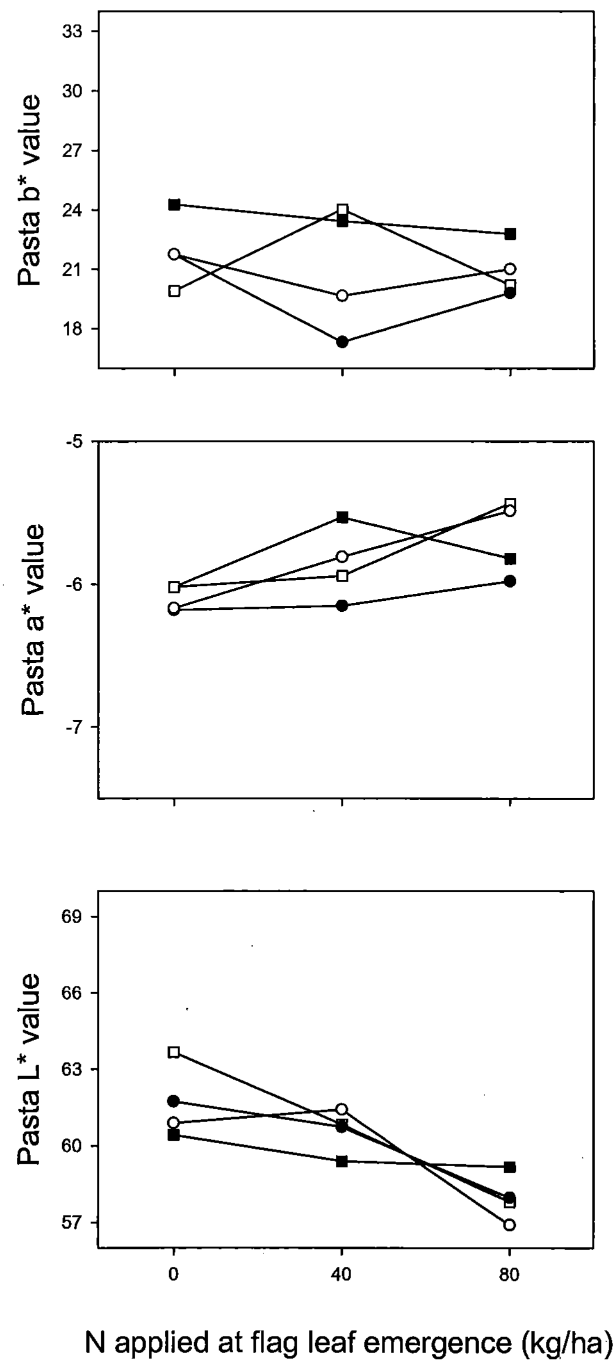

Figure 4.23 Relationships between mean pasta L* a* b* values at Lincoln for 'CRDW17' ( ) and 'Waitohi' (●) durum wheat and late N application (flag leaf emergence) rate after early N (tillering) had either not been applied at all (open symbols) or had been applied at 175 kg/ha or not at all (open symbols). LSD represents maximum error for the three-way interaction.

4.6.1.2 a* value

At Darfield, pasta a* values were affected by the interaction ($p<0.05$) between the effects of early and late N application (Figure 4.22). Where there was no early N applied, late N decreased mean a* values. In contrast, early N followed by any late N increased pasta a* values by about 0.4 units over both cultivars (Figure 4.22). Also at Darfield, there was a significant cultivar main effect with 'Waitohi' (-6.5) having a higher ($p<0.05$) mean a* value than 'CRDW17' (-6.7). For pasta a* values at Lincoln, there was no consistent effect of any N application and there was no difference between the cultivars (Figure 4.23).

4.6.1.3 L* value

At Darfield, early N alone decreased ($p<0.05$) pasta L* values by about one unit for both cultivars (Figure 4.22). At Lincoln, values for 'CRDW17' were decreased when only early N was applied but were slightly increased for 'Waitohi' (Figure 4.23).

4.6.2 Correlation between grain and pasta colour

There was a negative correlation between grain b* and pasta b* values ($r = -0.065$) (Figure 4.24). The highest grain b* value corresponded to the lowest pasta b* value, and this occurred for a 'Waitohi' crop which had no early N applied. However, it was a 'CRDW17' crop which had early N applied that produced the highest pasta b* value.

There was a poor correlation between pasta a* and grain a* values (r = 0.053) and there was no consistent effect of early N application or cultivar on the correlation.

The correlation between grain and pasta L* values was the strongest of the three colour parameters at r = 0.484. The lowest grain L* values were from crops that had early N applied, and these also produced low pasta L* values. 'Waitohi' crops with no early N applied had the highest pasta L* and grain L* values.

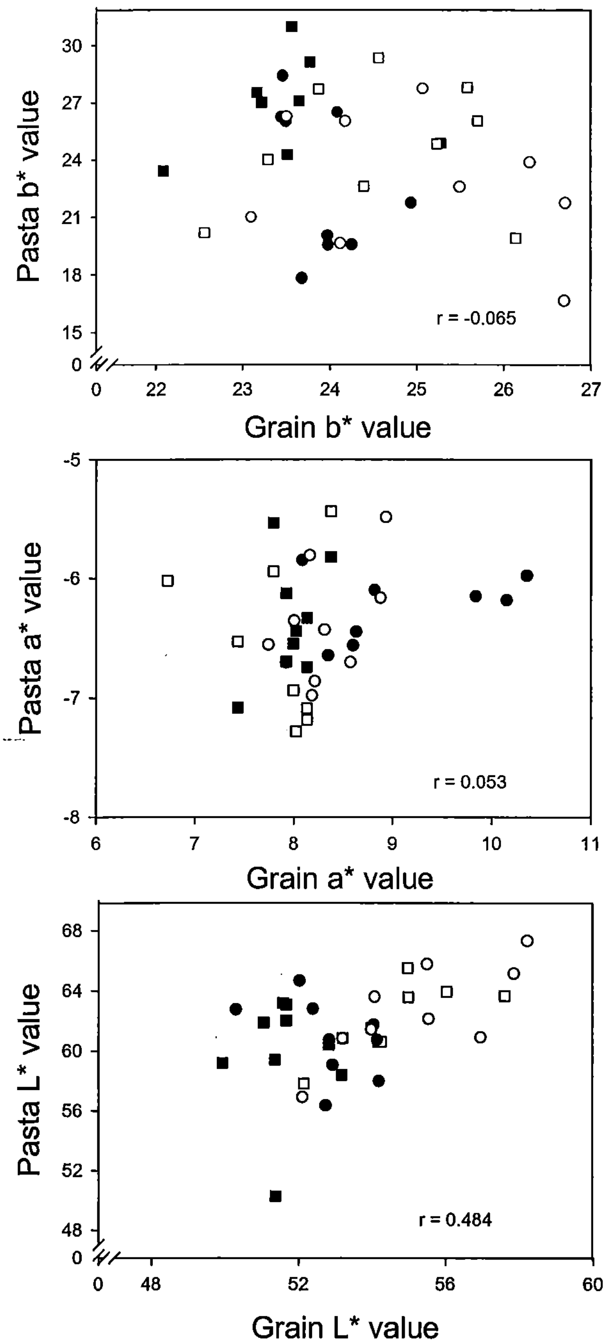

Figure 4.24 Relationships between grain L*, a* and b* values and corresponding pasta values for durum wheat ('CRDW17'(■) and 'Waitohi'(●)) grown in Canterbury with either early (tillering) N applied (closed symbols) or with held (open symbols).

4.6.3 Correlation between flour and pasta colour

Despite the lack of correlation between flour and pasta b* values (r = 0.18), the difference between cultivars was apparent with 'CRDW17' having higher values than 'Waitohi' (Figure 4.25). The lowest pasta and flour b* values were produced by 'Waitohi' crops without early N applied. 'CRDW17' crops which had early N applied had the highest pasta and flour b* values.

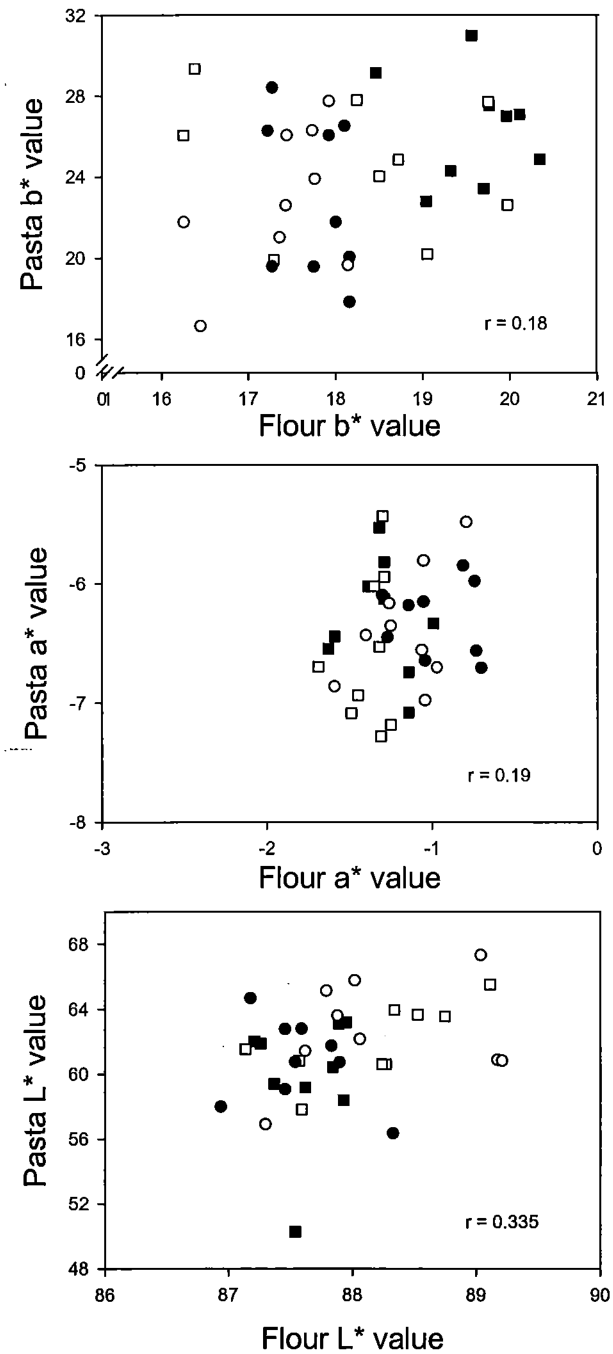

Figure 4.25 Relationships between flour L*, a* and b* values and corresponding pasta values for durum wheat ('CRDW17'(■) and 'Waitohi'(●)) grown in Canterbury with either early (tillering) N applied (closed symbols) or withheld (open symbols).

Differences between the cultivars were more pronounced for the relationship between flour and pasta a* values (r = 0.19) (Figure 4.25). 'Waitohi' tended to have a higher flour a* value than 'CRDW17', despite the pasta a* values being similar. There did not appear to be any consistent effect of N treatment on the pasta or flour a* values.

The correlation between flour and pasta L* values (r = 0.335) indicated an effect of early N application on flour L* values (Figure 4.25). When early N was applied, flour L* values were lower for both cultivars, but pasta L* values were unaffected.

CHAPTER 5

Discussion

5.1 Yield

5.1.1 N management for grain yield

Durum wheat growers have two management options available to them to increase yield and quality of durum wheat, N management and cultivar selection. The first objective for the project was to generate variability in grain yield. This was achieved using N management. Yields ranged from 2.8 to 8.2 t/ha across the three sites. Early N application increased yield from about 3.5 t/ha to over 5.0 t/ha at the dryland Darfield site and from 5.0 t/ha to over 7.0 t/ha with irrigation at Lincoln (Figures 4.1 and 4.2). These results support the initial hypothesis that yield can be increased with early N management, which agrees with the general finding by Stephen *et al.* (1985) that N applied at tillering has the greatest influence on grain yield. This is because early N increases the photosynthetic area of the plant and can also increase the efficiency of the conversion of intercepted radiation into biomass if N is deficient (Hay and Walker 1994).

Split early N applications are used to ensure that N is taken up efficiently by growing crops, particularly early in the season when the biomass is low. Early N was applied in three split applications at Darfield and Lincoln and two split applications at Wakanui. This was done to reduce the risk of loss via leaching.

The amount of N applied in the early fertiliser application treatments was based on pre-sowing measurements of available soil N and estimated water availability at each site. At that stage the initial site yield potential was estimated at 3 to 4 t/ha at Darfield, 4 to 5 t/ha at Lincoln and 6 to 8 t/ha at Wakanui. The accuracy of these estimates can be assessed by comparing them with the yield achieved in the control treatment at each site. At Darfield this was about 3.5 t/ha (Figure 4.1); at Lincoln it was 4.3 t/ha (Figure 4.2); and at Wakanui it was about 7.5 t/ha (Figure 4.3).

Management of N is more difficult on a dryland site than where water is guaranteed by irrigation. Primarily it is the rainfall during the season that sets the upper yield potential for a dryland crop. The amount of N applied to the site is related to the water available for crop growth.

On irrigated crops the influence of variable rainfall is reduced when the N fertiliser rate is determined because yield potential is not restricted by water availability. In this experiment the decision about the late N application at Darfield depended on early season rainfall and, therefore, soil moisture at flag leaf emergence. If the soil moisture had been low, the late N application would have been withheld because inadequate water availability to the crop would have restricted its ability to use the N efficiently. However, rainfall in November at Darfield was 111 mm (Table 3.3) so soil water availability was expected to support a high yielding crop. Therefore, the late N was applied.

The effect of early N on grain yield at the irrigated Wakanui site differed from that at Darfield and Lincoln. At Wakanui an early application of 150 kg N/ha decreased the yield of 'CRDW17' by 1 t/ha but it slightly increased the overall yield of 'Waitohi' (Figure 4.3). At this site the available soil N status was estimated to be 236 kg N/ha prior to sowing (Table 3.2) and a base dressing of 50 kg N/ha was applied to the whole experimental area at sowing. The lack of influence of N application on grain yield probably occurred because there was no N deficiency at this site. In non-limiting water situations and on N rich sites, there is usually no significant yield response to applied N (Drewitt and Smart 1981).

The early N by cultivar interaction resulted from a small yield advantage for 'Waitohi' over 'CRDW17' at Wakanui. However, this did not occur at the other sites where there was no yield difference between the cultivars. Therefore, the overall yield potential of the cultivars across these sites was similar. Thus, cultivar selection could be based primarily on grain and flour quality attributes, with lower emphasis on yield differences.

5.1.2 Total dry matter yield

At Darfield and Lincoln the total dry matter (TDM) yield followed similar trends to grain yield. Early N increased the TDM by 4 to 6 t/ha at both sites, and there were no differences between the cultivars (Figures 4.1 and 4.2). At Wakanui, the TDM was increased by over 4 t/ha for 'Waitohi' after early N application but it remained unchanged for 'CRDW17' (Figure 4.3). An increase in TDM was expected due to N application generally escalating yield by increasing photosynthetic area.

5.1.3 Harvest index

Differences in grain and TDM yields caused by the treatments resulted in a wide range of harvest index (HI) values (33 to 54%). Dougherty *et al.* (1975) reported values of HI ranging from 36 to 49% for three spring wheat cultivars grown in Canterbury. The large range in HI values was probably a result of the different growing environments at each site. At Darfield the early N main effect decreased the HI from about 39 to 34% (Figure 4.1), whereas at Wakanui the HI values decreased from about 45 to 40% after early N application (Figure 4.3). The low HI values at Darfield probably resulted from water limitations during grain-fill causing lower TGW when early N was applied. The carbohydrate supply may not have been sufficient to fill the grains due to the higher ear population in that treatment (Table 4.1). In support of the results of this study, Dougherty *et al.* (1975) found that the mean HI decreased from 43 to 39% when 200 kg N/ha was applied. Early N increased both grain and TDM yields, through the production of secondary and tertiary tillers in the crop. Although the higher order tillers produced extra yield, they produced fewer grains than the mainstem. Consequently the tiller HI, and therefore the crop HI were both reduced. Grains on the mainstem are often bigger than those on tillers because they have a longer duration to fill the grains with assimilate than secondary tillers. The thermal time from anthesis to physiological maturity is 650 °C days (Moot *et al.* 1996). The development of higher order tillers is accelerated in chronological time so that they mature within this thermal time. Therefore, the secondary and tertiary tillers have a shorter duration in the grain-fill stage. This may result in smaller grains and a lower number of grains/ear. Analysis of yield components enables a description of the observed differences to further explain the effects of N management.

5.2 Yield components

Individual yield components were analysed to understand how the yield of each cultivar responded to the N treatments. The response of individual yield components to N application differed across each site and between cultivars.

5.2.1 Ear population

The number of ears/m^2 responded differently to the N treatments across sites and between cultivars. At all sites, 'CRDW17' produced more ears/m^2 than 'Waitohi'. At Darfield 'CRDW17' produced 895 ears/m^2 compared with only 688 for 'Waitohi' (Table 4.1). At Lincoln 'CRDW17' produced 928 ears/m^2 which was about 100 ears/m^2 more than for 'Waitohi' (Table 4.2). Similarly, the mean number of ears/m^2 for 'CRDW17' was 85 more than for 'Waitohi' (Table 4.3) at Wakanui.

The response of ear population to N treatments differed among sites. At the dryland Darfield site, early N application did not consistently influence the number of ears/m^2. Where no early N was applied, late N increased the number of ears/m^2 for 'CRDW17', but decreased it for 'Waitohi'. However, at Lincoln only late N application increased the ear population (Table 4.2), and at Wakanui early N increased the number of ears/m^2 for both cultivars (Table 4.3).

The population achieved by 'CRDW17' and 'Waitohi' at all sites was much higher than comparable values for conventional bread spring wheats in New Zealand. For example, Dougherty *et al.* (1975) found between 453 and 588 ears/m^2 for irrigated wheat crops grown under two N fertiliser treatments in Canterbury. However, durum wheat typically has a population around 600 to 800 ears/m^2 or higher (Hanson pers. comm.).

Ear population has the advantage of being easy to determine, and it was been suggested that it is a good predictor of total yield (Hampton *et al.* 1981). However, the results of this study do not support this suggestion, because ear population was not related to yield. For example, there was a significant ear population difference between cultivars, but no grain yield difference. Both cultivars produced a similar grain yield increase from early N applications but the N increased different yield components. For 'CRDW17' the higher yields were associated with increased ears/m^2 when early N was applied, but this was not the case for 'Waitohi'.

5.2.2 Grains/ear

At each site the mean number of grains/ear was higher for 'Waitohi' (13) than 'CRDW17' (9). At all sites early N application affected the number of grains/ear (Tables 4.1, 4.2 and 4.3). At Darfield and Lincoln, early N increased grains/ear for both cultivars. In contrast, at Wakanui grains/ear was decreased by early N application for both cultivars.

Grains/ear is the product of the number of spikelets per ear initiated during crop development and the number of grains that are produced in each spikelet. In N deficient soils, N fertiliser applied prior to the double ridge stage can add an extra 2-3 spikelets per ear (Scott *et al.* 1992). In the present study, early N was applied at tillering, before double ridges. The number of grains per spikelet can also be increased by early N application (Scott *et al.* 1992), through improved floret growth and development which occur subsequently (Langer 1979). Hence the overall effect of N applied to N deficient soils at tillering is often an increase in the number of grains/ear. Results from Darfield and Lincoln support this, as both sites were N deficient when N was applied at tillering (Table 3.2). However, the initial available soil N at Wakanui was high and further N application at tillering did not increase grains/ear for either cultivar.

The higher grains/ear for 'Waitohi' than for 'CRDW17' may indicate that 'Waitohi' produces more spikelets/ear and/or more grains/spikelet than 'CRDW17'. However, in comparison with bread spring wheat cultivars, the numbers of grains/ear produced by 'Waitohi' and 'CRDW17' were low. The mean values found by Dougherty *et al.* (1975) ranged from about 19 to 23 for spring bread wheat grown with N fertiliser in Canterbury. The numbers of grains/ear were low in 'CRDW17' and 'Waitohi' because the ear population and TGW were both much higher in these cultivars than are usually found in conventional spring bread wheat. The number of grains/ear is low for durum wheat because the amount of assimilate partitioned to support an increase in grains/ear is reduced to compensate for the high assimilate demand from the high ears/m^2 population and TGW (Power and Alessi 1978).

5.2.3 Thousand grain weight (TGW)

The effect of early N application on TGW differed among sites and between cultivars. In most cases, there was a decrease in TGW with early N (Tables 4.1, 4.2 and 4.3). This was consistent with previous studies which have found that N applied at tillering generally decreases grain weight (Drewitt and Dyson 1987) or has little effect (Martin *et al.* 1992). The increase in ear population caused by early N application decreases the TGW as the crop produces more ears with fewer, smaller grains (Power and Alessi 1978). In support of this theory, the lowest TGW values were at Wakanui where the crop had the highest ear population and, hence, had smaller grains.

'CRDW17' consistently had a higher TGW than 'Waitohi' at all sites. Gallagher *et al.* (1975) found that TGW was determined primarily by the genetic makeup of the cultivar. Despite the inconsistent effect of N treatments on TGW in this study, typically the TGW of a cultivar responds to environmental influences, such as N availability (Martin *et al.* 1992). However, in this study TGW was not a good predictor of how N fertiliser will affect the overall yield when different cultivars are being studied, due to the effect being cultivar dependent.

There was no consistent effect of late N application on the TGW at Darfield and Lincoln. However, at Wakanui the late N by cultivar interaction occurred because the TGW for 'CRDW17' decreased with increasing N, but N had no effect on 'Waitohi' (Table 4.3). A late application of N usually increases grain weight (Drewitt and Dyson (1987); Martin (1987)). The results from this study contrast with results from

Martin *et al.* (1992) where an average 1.5 mg increase in TGW was found across cultivars (Table 2.2) when N was applied at booting. The lack of late N effect might be because, in most cases, the genetic potential for grain size of the two cultivars was achieved, and no further increase was possible.

5.2.4 Grains/m^2

The individual yield components for both cultivars were poorly correlated with the overall yield at each site. The variable nature of both grains/ear and ears/m^2 and plasticity among components means that they are not related consistently to grain yield. In addition, in this study TGW was determined primarily by the genetic make-up of the cultivar so is not related consistently to yield. However, the product of grains/ear and ear/m^2 is grains/m^2 which was related closely to grain yield for both cultivars under different N treatments. For example, at Darfield and Lincoln, early N increased yield for both cultivars, but the ways in which each cultivar achieved the yield increase was different. In most cases, 'CRDW17' had more ears/m^2 than 'Waitohi' (Tables 4.1 and 4.2), whereas 'Waitohi' had more of grains/ear. The combined effect of these responses to early N was that both cultivars had a similar number of grains/m^2 and similar grain yield. Grains/m^2 is often the component that is related most consistently to yield. Therefore, it is the one that is often predicted in crop models. For example, grains/m^2 was used by Jamieson and Wilson (1992) when they investigated the physiological and agronomic limits to wheat yield and quality. The results from this study support the use of grains/m^2 as a predictor of grain yield.

The use of any one yield component to predict final crop yield does not consider the plasticity among components. It is the resources available to the crop during growth (water, N availability, etc) which determines the final yield rather than the number of any one component produced. Thus, in determining how the final yield is constructed mutual compensation occurs among cultivars, with different cultivars interacting in different ways to the changing environment. Therefore, the structure of final yield may differ substantially among cultivars and between different growing environments. Individual yield components considered in isolation do not account for this compensation and cannot be used in isolation to predict yield. Therefore, the use of a combination of components such as grains/m^2 as a predictor of yield is logical, because it is more stable between environments due to the compensation between individual components.

5.3 N budget

At each site there was a large range in vegetative N contents (0.29-1.42%). Combined with the fertiliser applications, these equated to the removal of 16 to 132 kg N/ha over all treatments (Tables 4.4, 4.5 and 4.6). Across all sites, the lowest vegetative N biomass content at final harvest came from treatments where no early N was applied. At all sites the vegetative N content was higher when early N was applied compared with no early N application. Less vegetative N may have been translocated to the grain when early N was applied, since more soil N was available. Fergusson (1999) found that more N was relocated from the biomass in barley when little or no N was applied during the season (Table 2.1).

'CRDW17' had a higher mean vegetative biomass N content than 'Waitohi' at all sites at physiological maturity. At Darfield, when no early N was applied the mean value for 'CRDW17' was 0.58% compared with 0.35% for 'Waitohi'. Similarly, at Wakanui the corresponding means were 0.82% and 0.58%. When early N was applied at both Darfield and Lincoln, the mean biomass content for 'CRDW17' was increased from about 0.40 to 0.85% compared to an increase from about 0.35 to 0.50% for 'Waitohi'. The low vegetative N content of 'Waitohi' may indicate that more vegetative N was translocated to the grain. This possibility was supported by the grain N values for the two cultivars.

'Waitohi' consistently had a higher grain N content than 'CRDW17' over all treatments. At Darfield, the value for 'CRDW17' was 1.83% compared with 1.98% for 'Waitohi' (Table 4.4). This indicates that 'Waitohi' could be more efficient at translocating N from the vegetative part of the plant to the grain than 'CRDW17'. Also, it may indicate that 'Waitohi' is more efficient at remobilising N in low N status soils than 'CRDW17'. The nitrogen harvest index (NHI) would be higher for 'Waitohi' than 'CRDW17' due to the greater ability of 'Waitohi' to remobilize N from the biomass to the grain.

5.3.1 Soil N testing

Most measured final soil N values at Darfield were within 30kg N/ha of those estimated in the N budget (Table 4.4). The estimated soil content was based on the initial soil N content as determined by soil N tests. These results support the suggestion by Stephen *et al.* (1997) that sampling of soil to 0.60 m depth is required to gauge the N content rather than a test on the 0.15 m depth which is commonly used. Both the soil sampling and laboratory testing procedures can cause variability in results. Soil N laboratory testing has a coefficient of variation of 18%, which equates to a potential variability of 36 kg N/ha in a soil test predicting a soil content of 200 kg N/ha. The 30 kg N/ha difference observed in some results in this study is within this range. In addition, the roots of wheat may extract N from greater than the 0.60 m depth that was sampled, thereby allowing more soil N resources to be used than was predicted in the test.

Overall, most final soil N values were slightly higher than those calculated by the N budget (Tables 4.4, 4.5 and 4.6). This may be due to more mineralisation of organic N occurring than was predicted by the soil tests taken before sowing. In particular, at Wakanui some final soil tests were up to 100 kg N/ha higher than the calculated values. It is possible that, at this site there was more N released from the breakdown of the roots and nodules of the previous white clover seed crop than was predicted by the initial soil test.

However, the final soil test results for Lincoln were also 30 to 100 kg N higher than the estimated values. The variability in the results from both Lincoln and Wakanui question the validity of soil N testing, but the results were useful for the initial planning of treatments in this experiment. Ultimately, the soil N status and N management influence grain quality.

5.4 Grain and flour quality

As there was no difference between the yield for both cultivars, cultivar selection can be based on the quality attributes of each cultivar. The payment growers receive for wheat is determined on both yield and protein content, so the ability of a cultivar to accumulate protein is an important parameter for growers to consider. By using a range of N treatments the quality attributes of each cultivar could be determined and compared. Hence, evaluation of the performance of each cultivar under different N management was possible by applying a range of N fertiliser treatments to generate variability in quality parameters.

5.4.1 Grain protein content

Variability in grain quality was achieved as shown by the range in grain protein content values (9 to 14%). As predicted, both early and late N application increased grain protein contents, as the control treatment at each site having the lowest protein content value (Figure 4.4). A single application of N at tillering increased protein content at each site by 2-3.5% for both cultivars. In New Zealand, the minimum grain protein content required for durum wheat is 11.5%. At all sites, each crop that had early N applied produced at least this standard and thus the late N application was not required to achieve the required protein concentration.

Nevertheless, as expected N application at flag leaf emergence did increase the grain protein content (Martin (1987); Scott (1981); Scott *et al.* (1992)) by a further 1% for both cultivars. In wheat sown in autumn the late N application is usually necessary to ensure that the protein content standard is met. Early N for a spring crop is applied 2 to 3 months later than 'early N' for an autumn crop. Therefore, for a spring crop it is likely that more of the early N is still present in the soil when the crop reaches the grain-fill stage, and therefore more will contribute to the grain protein content. This is not usually the case for an autumn sown crop because early N that is not used for growth is often leached during the wet winter months or used by the rapid spring growth. Hence, the early N applied to an autumn sown crop is much less likely to increase the protein content of the grain.

Grain protein content values for 'Waitohi' were usually about 1% higher than for 'CRDW17' (Figure 4.4), and this was consistent with the higher NHI for 'Waitohi'. The implication was that 'Waitohi' partitioned more of the available N into protein than 'CRDW17', and this supports the hypothesis that there might be a cultivar difference for protein accumulation.

5.4.2 Flour protein content

Flour and grain protein contents were strongly correlated (r = 0.80) (Figure 4.10). However, flour protein content values were at least 1% lower than the corresponding grain values, primarily due to the removal of the bran (Moyle pers. comm.) and embryo.

Grain and flour protein contents are important parameters for the miller as they largely determine the quality of the end product. For durum wheat, protein content is important because it is related positively to pasta cooking quality (Matsuo *et al.* (1972); Dexter and Matsuo (1977)). For a grower to obtain optimum yield and protein concentration, suitable N management suited to the individual paddock is required. At all sites this was achieved by the application of early N at tillering, which increased both grain yield and protein content of the grain and flour (Figure 4.11). However, cultivar selection is not solely based on yield and protein accumulation, other quality parameters are also important to consider. For the grower other favourable agronomic traits are particularly important such as grain soundness, or resistance to sprouting.

5.4.3 Grain falling number

During the 1999/2000 season, the wet summer (Table 3.3) caused damage to the grain resulting from premature germination (sprouting) at all sites (Table 4.7). The summer rainfall led to increased variability in falling number results which, in turn, increased the variability in grain quality and allowed further cultivar evaluation based on sprout susceptibility.

The difference between cultivars suggests that 'CRDW17' was more susceptible to sprouting than 'Waitohi' presumably because its moisture and humidity requirements for sprouting are lower. Hence 'CRDW17' reaches its threshold for sprouting earlier than 'Waitohi'. It would be expected that 'Waitohi', which matured about 1 week earlier than 'CRDW17', would have increased susceptibility to sprouting during the wet period. Results did not support this, as 'CRDW17' consistently had a lower falling number at each site despite its later maturity.

Industry requires a falling number value of 250 s or higher for grain to be accepted for milling and pasta making. Pasta processing problems with sprouted grain include uneven hydration and extrusion, strand stretching, and a high potential for checking and cracking upon storage (Dexter *et al.* 1990). It is important for a grower to be aware of the susceptibility of a cultivar to sprout damage to allow an informed choice of cultivar at sowing especially if summer rainfall often occurs where the crop is to be grown. This would make sprout resistance a key requirement for any cultivar.

5.4.4 Flour falling number

In most cases, the flour falling number results followed similar trends to the corresponding grain values. However, flour falling number values were between 10 to 50 s higher than the grain falling number values (Table 4.8). This was due to the removal of aleurone, embryo-scutellum and adjacent endosperm, and these wheat components generally contain higher levels of α-amylase (Moot and Every 1990) than the endosperm. The removal of these fractions during milling increases the falling number value due to the reduction of α-amylase enzyme concentration.

5.5 Flour rheological testing

5.5.1 Water absorption

The effect of early and late N applications on water absorption differed for Lincoln and Darfield. For example, at Lincoln both early and late N application increased water absorption, but this was not the case at Darfield. In general, the water absorption values (Table 4.9) were lower than the industry target range of 70 to 74%. The low values and the inconsistent effect of N application may be a result of many samples being too compromised by sprout damage, but to varying degrees.

5.5.2 Dough stability time

The target range for stability time used by industry is between 5.0 and 9.0 minutes. None of the samples from the experiments were above the range although some were lower than preferred by industry. Flour stability time is a measure of flour strength (Moyle pers. com.), which is related directly to gluten content. Flour strength is also a function of the amount of starch which has been broken down by α-amylase during sprouting, as starch is the 'scaffolding' in the dough and thought to be important in the formation of gluten sheets (McGee 1991). Thus, the lower dough strength for 'CRDW17' may be an artefact of its low falling number. Different results may have occurred in the absence of sprouting.

5.5.3 Dough development time

The longer development time for 'Waitohi' suggests that either it had more or stronger gluten than 'CRDW17'. The protein composition of grain is fundamental in determining the physical properties of the dough (Stone and Savin 1999). As a rule, the greater the molecular mass of the proteins accumulated in the grain, the greater the strength of the resulting dough. The protein fraction with the highest molecular mass is the glutenins (Stone and Savin 1999), and the higher protein content of

'Waitohi' may come from a higher proportion of glutenins in the grain than 'CRDW17'.

5.6 Grain colour

5.6.1 Grain b* value

Early N application was the agronomic treatment that gave the optimum yield and achieved the required protein content but it also resulted in a considerable decrease in grain yellowness (Figure 4.5).

The inconsistent effect that late N application had on grain b* values suggests that grain yellowness is not a stable parameter that would be suitable to use to determine the quality of grain.

'Waitohi' had higher grain b* values, or grain yellowness, than 'CRDW17' when averaged over all N treatments at both Lincoln and Wakanui. This difference between cultivars indicates that 'Waitohi' partitions more of its yellow carotenoid pigments into the aleurone (bran) layer than 'CRDW17'.

5.6.2 Grain a* value

The effect of N treatments on grain a* values was also inconsistent. However, 'Waitohi' tended to have more enhanced grain redness, or higher grain a* values, than 'CRDW17' regardless of N treatment at each site (Figure 4.6). Therefore, both the grain yellowness and redness were higher for 'Waitohi' than 'CRDW17'. This is most likely due to the genetic make-up of 'Waitohi' enhancing the yellow-red colour of the bran more than 'CRDW17'. In general, the grain colour for 'Waitohi' is closer to the yellow-red border on the CIELAB colour space than 'CRDW17'. To investigate the combined effect of a* and b* values, transformations were carried out to determine the hue angle and chroma of each sample.

5.6.3 Grain hue angle

The hue angle of a sample is described by a single-word such as red, blue, yellow, etc. The results for hue angle followed trends similar to the grain b* results, which was predictable due to the lack of variation in the grain a* values.

At all sites, the highest hue angle was achieved where there was no early or late N applied (Figure 4.7). At both Lincoln and Wakanui sites, there was also a cultivar effect with 'CRDW17' having a higher mean hue angle than 'Waitohi'. In addition, the application of N at tillering decreased the hue angle for each cultivar by between 1-3 units. A higher hue angle corresponds to a lower a* value and a higher b* value, which results in a more preferred colour. These results were supported by Penno (1996) who found that an oat groat with a high a* value also had a low hue angle which was a move away from the preferred colour.

5.6.4 Grain chroma

Chroma, saturation or purity of colour relates to the intensity of the colour received. The highest grain chroma values were achieved where no N had been applied to either cultivar (Figure 4.8). In support of the similarity between hue angle and b* values, grain chroma values also followed similar trends to the grain b* values due to the lack of variation in grain a* values. Results from groat colour analysis on oats concluded that the preferred colour was not related to the degree of colour saturation (Penno 1996).

5.6.5 Grain L* value

The L* value of a sample represents its lightness or reflectance, with black being zero and white being 100. The lightest coloured grains were produced when no early or late N was applied at each site. Where N was only applied at tillering or only at flag leaf emergence, grain L* values decreased at all sites (Figure 4.9). The decrease in grain L* values with N application may be attributed to the decreased TGW, indicating a lower volume to surface area ratio of white endosperm to dark bran.

Other environmental factors apart from N availability can also affect grain colour. These were not taken into account in the present study but may have contributed to some of the variability in the grain colour results. For example, Laignelet (1983) reported that heavy rain during ripening resulted in grain that was whiter in appearance and less vitreous. Furthermore, fungal diseases can have a major impact on grain colour. For example, an increase in darkness of a grain sample can occur after black point infection (Cromey and Mulholland (1988); Penno (1996)) and Fusarium infection can cause an increase in grain redness (Dexter *et al.* 1997). However, it is the colour of the flour and subsequent pasta, rather than grain that is of primary importance to industry.

5.7 Flour colour

5.7.1 Flour b* value

At each site, the highest flour b* value was achieved by a 'CRDW17' crop that had early N applied. Therefore, the hypothesis that N availability may influence flour yellowness is supported by these results, and they open up the possibility that growers may be able to manipulate colour through N fertiliser management. In general, the single early N application increased the yellowness of the flour by between 1-3 units for both cultivars at each site. The way early N affects flour colour is not fully understood, but it may be due to the higher vegetative N content at anthesis allowing an increased carotenoid synthesis during grain-fill.

For most treatment combinations, flour b* values were higher for 'CRDW17' than 'Waitohi' (Figures 4.12). The increased yellowness of the flour for 'CRDW17' makes it the cultivar of choice by industry as yellow flour is considered desirable in the production of pasta. It is likely that the genetic make up of 'CRDW17' enhances the yellowness of the endosperm by one of two possibilities. It could be that 'CRDW17' deposits more of the synthesised carotenoid pigments in the endosperm instead of in the bran layer than 'Waitohi'. The fact that 'Waitohi' had higher grain b* values than 'CRDW17' supports this theory. The second possibility is that 'CRDW17' may synthesise more carotenoid pigments than 'Waitohi'. Although the carotenoid content of the flour was determined (Figure 4.20), the total synthesised carotenoid pigment was not calculated because carotenoid content of the bran was not measured.

In addition, the low extraction rate of the milled samples may have confounded results if the cultivars stored their carotenoid pigment in different locations in the grain. The extraction rate in this experiment ranged from 27 to 63%, with an averaged of 40%. These values are much lower than the 72% usually achieved in New Zealand industry mills (Moyle pers. comm.) due to test mills not being suitable for milling hard durum wheat. There was no difference noted between cultivars for extraction rate but it is possible that results may have changed if a higher extraction rate was achieved. For example, if the carotenoid content for 'Waitohi' was located closer to the embryo than 'CRDW17' then a higher extraction rate may have resulted in 'Waitohi' having a more desirable flour colour.

There was a negative correlation between grain and flour b* values at all locations (Figure 4.13). (r = –0.25 to –0.47). However, the relationship was not strong, indicating that grain b* values would not be good predictors of corresponding flour b* values, especially at the low extraction rates achieved in this experiment.

5.7.2 Flour a* value

The higher a* values, or flour redness, for 'Waitohi' than 'CRDW17' are likely to be due to the genetic make-up of the cultivars (Figure 4.14).

There was a weak correlation (r= 0.21 to 0.45) between grain a* and flour a* values (Figure 4.15), giving some indication of a link between the two but the relationship was not strong enough to be able to use grain a* values to predict flour a* values.

However, there was a relationship between flour a* and b* values. 'Waitohi' flour had higher a* values and lower b* values than 'CRDW17'. The two colour parameters could be related which may mean that the preferred flour colour may not be high b* values, but could actually be a move away from the red to the yellow region on the colour space (Figure 2.3). This was found to be the case for oat groat colour (Johnson *et al.* 1997). Again, transformations were carried out on the combination of flour a* and b* values to determine the hue angle and chroma values.

5.7.3 Flour hue angle

The magnitude of the effect of N fertiliser on hue angle differed among sites and was cultivar dependent (Figure 4.16). In most cases, 'CRDW17' with no N applied had the highest hue angle. In contrast, the highest flour b* value was achieved by 'CRDW17' that had early N applied. Late N applications reduced the hue angle for both cultivars at Lincoln, but was not at Darfield and Wakanui. There seemed to be a negative relationship between flour hue angle and flour a* values. For example at

Lincoln late N increased the flour a* values for both cultivars, but decreased their flour hue angles.

Assuming that a* and b* values are appropriate measures of the colour of a sample, then it may be best to integrate a* and b* values, and use hue angle as the preferred method of colour determination. This would be a valid option if there was a consistent relationship between preferred colour and a move away from the red region of the colour space into the yellow region. Penno (1996) reported a negative relationship between the colour of preference (yellow) and hue angle in oat groats, because as the point shifts from red to yellow around the circumference it goes from inferior to preferred colour (Figure 2.4).

However, if the preferred colour was not related to the redness of the sample, the inclusion of a* in the colour determination may adversely affect the colour measurement. In either case, the use of hue angle instead of individual a* and b* values would need to be evaluated and confirmed using a test panel. Consumers and people involved in the pasta industry would be required to rank a selection of grain and flour samples which have varying hue angle values. However, the high variability in hue angle responses to N treatments across sites may indicate that it is not appropriate to be used as a descriptor of colour.

5.7.4 Flour chroma

The flour chroma value for 'CRDW17' was higher than 'Waitohi' at all sites regardless of N treatment (Figure 4.17). 'CRDW17' had the highest chroma values when early N was applied. Flour chroma followed similar trends to the flour b* values explaining the cultivar main effect at each site. However, due to the variability in flour chroma results between sites, it did not appear to be a useful measure for describing colour preference in flour samples.

5.7.5 Flour L* value

Despite the emphasis on b* and a* colour values, L* (lightness or reflection) is a critical component in the colour space. Early N application alone decreased the flour L* values for both cultivars at all sites (Figure 4.18). However, there was no difference between the cultivars. Analysis of the relationship between grain and flour L* values gave correlation coefficients in the range from 0.50 to 0.68 (Figure 4.19). Of the three colour variables (L*, a* and b*), this was the strongest correlation between grain and flour values.

However, this relationship is not useful for using grain L* values to predict colour preference in flour because L* is not related directly to the yellow or red region on the chart, which is why there was no L* difference between cultivars. The results from this study agree with Penno (1996) who reported that neither chroma nor L* values were related to colour preference.

5.7.6 Flour carotenoid content

The carotenoid pigments are the primary causes of grain, flour and pasta yellowness (Markley and Bailey (1935); Lepage and Sims (1968)). The concentration of carotenoid pigments in the flour was determined to establish whether there was a relationship between flour colour values and carotenoid content.

At both Lincoln and Darfield, 'CRDW17' had a higher carotenoid pigment content than 'Waitohi' (Figure 4.20) regardless of the early N status. The difference between cultivars confirms that 'CRDW17' has a higher amount of pigment partitioned in the endosperm, although 'CRDW17' does not necessarily synthesise more carotenoid pigments than 'Waitohi'. However, Irvine and Anderson (1953) demonstrated that there was a highly significant difference among durum wheat cultivars in their grain carotenoid contents. Thus, the selection of 'CRDW17' for increased yellow colour is likely to have been based on a higher carotenoid content.

For both cultivars, the correlation between carotenoid pigment content and flour L* ($r = -0.10$) and a* ($r = -0.39$) values was weak. However, there was a moderate correlation ($r = 0.58$) with flour b* values (Figure 4.21). The corresponding difference seen in carotenoid content and flour b* values between cultivars supports the use of flour b* values as a preliminary predictor of pasta yellowness, rather than L* or a* values. This analysis confirms that discrimination between flour yellowness values by the b* component is based on carotenoid pigment concentration.

Destruction of carotenoids may begin during grain storage and then increase further during and after milling when the cellular structure has been disrupted (Laignelet 1983). During milling, depending on extraction rate, a variable amount of these pigments may be lost initially. In addition, there is a large decrease in carotenoid pigment content during pasta processing. The loss of carotenoid content during milling is small compared with the loss during pasta extrusion. For example, Borrelli *et al.* (1999) calculated that a 7.9% loss of β-carotene occurred during milling compared with 16.3% lost during pasta making.

5.8 Pasta quality

5.8.1 Pasta b* value

Trends in pasta colour were similar to the flour colour results. In most cases, pasta b* values were increased when only early N was applied. However, the increases were not significant, probably because there was insufficient replication of pasta samples for colour testing. If time had permitted extrusion of more samples, variability may have been decreased by having more replicates. However, initial results are encouraging because they indicate that there may be potential to improve pasta yellowness through N management.

In most cases, 'CRDW17' had mean pasta b* values from 0.5 to 3.0 units higher than 'Waitohi' (Figures 4.22 and 4.23) regardless of N treatment. This supports the use of 'CRDW17' in industry because of its better pasta colour, and provides an option for growers to increase pasta yellowness by choosing 'CRDW17' instead of 'Waitohi'.

5.8.2 Pasta a* value

The effect of N application on pasta a* values, or redness, differed among cultivars and sites (Figures 4.22, 4.23).

The lack of conformity among pasta a* results may have been due to the browning of pasta samples by LOX activity. The drying process may have triggered browning to occur in the pasta samples which would be detected as increased redness, and would explain the inconsistencies in the pasta a* values.

5.8.3 Pasta L* value

The effect of N treatments on pasta L* results was also inconsistent. For example, at Darfield early N application alone decreased the mean pasta L* value by about 1 unit. In contrast, at Lincoln, the mean pasta L* was decreased by early N application to 'CRDW17' but it was slightly increased for 'Waitohi'. The inconsistent results might be due to the effect of any LOX activity that may have caused bleaching or browning during pasta processing. LOX catalyses the addition of molecular oxygen to fatty acids. The fatty acid radicals produced from this addition are responsible for the oxidative degradation of pigments such as xanthophylls, β-carotene and chlorophylls (Borrelli *et al.* 1999), resulting in an overall bleaching of durum products. The extent of carotenoid loss during pasta making differs among cultivars and may range from 30% to 60% in some cultivars (Irvine and Anderson 1953).

5.9 Colour relationships

5.9.1 Grain and pasta colour

There was a weak negative correlation between pasta and grain b* values (r = -0.065). This was expected as a result of the negative correlation between grain and flour b* values, and pasta b* values followed trends similar to the flour b* values. In addition, the correlation between pasta and grain a* values was weak (r = 0.053), indicating that grain redness has little effect on the overall pasta redness (Figure 4.24).

However, the correlation between grain and pasta L* values was the strongest of the three colour components (r = 0.484). However, in general, grain colour was not a good predictor of pasta colour. This was expected as the aleurone (bran) layer of the grain is not present in the final pasta product.

5.9.2 Flour and pasta colour

The lack of correlation between pasta and flour b* values may have been due to the LOX enzyme generating variability in pasta yellowness by bleaching the pasta products. This activity may also explain the lack of correlation between pasta and flour L* values. In addition, there was no correlation between pasta and flour a* values (Figure 4.25) which is probably due to the browning that is often encountered with pasta making.

Apart from the significant difference between cultivars for the b* values, other flour colour differences between them did not translate into pasta colour. It may be that one cultivar has a higher concentration of LOX enzyme in its dough than the other. If this was the case then the paler colour of 'Waitohi' flour and pasta might be due to a higher amount of carotenoid pigment degradation from LOX bleaching reactions. In addition, the redder colour of 'Waitohi' pasta may also be a function of the increased browning initiated by LOX during pasta processing. This may also be cultivar specific.

5.10 Conclusions

- N applied at tillering increased yield the most when the soil was N deficient. There was no yield difference between cultivars at any site. However, the cultivars differed in the way that their yield components responded to N fertiliser application. In both cases, the number of grains/m^2 was the most stable component of grain yield. All other yield components exhibited substantial plasticity.
- Durum wheat had larger TGW and more ears/m^2 than most bread wheat cultivars. Both of these components responded to environmental influences but they were also strongly genetically determined.
- In general, both early and late N applications increased grain and flour protein contents when the soil was N deficient.
- 'Waitohi' consistently had a higher mean protein content than 'CRDW17'.
- 'Waitohi' consistently had higher falling number values than 'CRDW17' at all sites and in hand and combined samples.
- N treatments did not consistently influence falling number values.
- Optimum N management to achieve high yield was not detrimental to flour/pasta colour. There was evidence that it can enhance colour as the highest flour and pasta b* values were achieved in the treatments where N was applied early. These treatments also increased yield and produced acceptable protein content.
- Selection of a cultivar with enhanced flour and pasta yellowness, such as 'CRDW17' is the most direct way to improve pasta yellowness.
- The lack of correlation between grain, flour and pasta colour variables means that grain colour testing cannot be used as an accurate predictor of pasta colour.

- The pasta yellowness difference between cultivars was related best to the flour b* values. Therefore, flour b* is a more appropriate measure of final pasta yellowness than grain b*.

CHAPTER 6 General Discussion

A major problem facing the New Zealand pasta industry is the inconsistent yield and quality of durum wheat grown in New Zealand. Consumers associate high quality pasta with enhanced yellowness. However, New Zealand pasta is paler in colour than similar imported products and, in some cases, is considered undesirable by consumers. In this study, high quality durum flour was defined as having a high (>11.5%) protein content (Figure 4.11), high (>250 s) falling number (Table 4.8) and a high (>18) b* value (Figure 4.12). Acceptable crops would also have desirable rheological properties such as a water absorption between 70 to 74%. The main research objective of the study was to determine if the two main management options available to growers, namely N management and cultivar selection, could be used to produce high yielding durum wheat that met the desired quality characteristics, including acceptable flour and pasta yellowness. The results from the field and laboratory testing were used to determine differences between N management treatments and cultivars. From these results, management strategies for growers to achieve high yields of high quality can be developed.

To investigate yield and quality differences between N treatments and cultivars, three field experiments were established at locations with varying yield potentials. These sites were selected with the intention of generating variability in final grain yield and protein results. A dryland site at Darfield was selected along with two irrigated sites, Lincoln and Wakanui. The lowest yield potential was estimated at the dryland Darfield (3 to 4 t/ha) site with higher yield potentials estimated at Lincoln (4 to 5 t/ha) and Wakanui (6 to 8 t/ha) sites. The yield potential of each site was estimated by taking into consideration the water availability and initial soil N content prior to sowing. Soil N testing was useful in determining the N fertiliser treatments required at each site to achieve the optimum yield potential. Both Darfield and Wakanui sites had higher initial soil N content (Table 3.2) than the Lincoln site. Despite the diversity between sites, crops of adequate yield were achieved at each site through the use of appropriate N management.

N management allows growers to obtain maximum profit from the payment schedule for durum wheat by producing high yielding crops of at least 11.5% protein with bonus payments for higher levels. In this experiment, optimal yields were achieved at each site by applying N at tillering. In addition, N applied at tillering increased grain protein to at least 11.5% at all sites, so all crops of wheat with early N would have been acceptable for pasta production regardless of whether late N was applied. However, a further N application at flag leaf emergence, following early N, continued to increase protein content. As well as increasing grain yield and protein content, N management also generated variability in grain and flour colour. In most cases, early N application decreased grain b* values, or grain yellowness, for both cultivars. Fortunately, there was a negative relationship between grain and flour b* values which resulted in early N application tending to enhance flour yellowness. In general, early N application also increased pasta yellowness. Despite an inconclusive relationship between flour and pasta colour, it is likely that a greater number of replicates would have established a positive effect of early N application on pasta yellowness. Overall it appears that early N was the N treatment that generated the greatest yield increase, achieved the minimum protein content required, and enhanced flour yellowness. This suggests that the current N management used by growers to achieve optimal yields is also the N management that achieves optimal quality.

The application of only N at flag leaf emergence failed to compensate for the yield loss where early N had been withheld. However, late N application was successful in increasing the grain protein content by about 1% for both cultivars at each site. There was no consistent effect of late N application on the grain or flour yellowness of either cultivar. Therefore, late N application was an effective N management tool for increasing grain protein content but had little effect on other quality parameters.

The other main management tool available to growers to achieve high yields and protein content is cultivar selection. Across the diverse sites used in this study there was no yield advantage to be obtained from selecting one cultivar over the other. This suggests that growers could select the durum cultivar they sow based on solely on the quality attributes of each cultivar. The results for protein content illustrated that 'Waitohi' consistently achieved a higher protein content than 'CRDW17'. Because growers are paid on yield and protein content, 'Waitohi' would be the cultivar of choice, 'Waitohi' achieved similar yields to 'CRDW17' but, under the same N management, was more efficient at partitioning available N to protein.

Other favourable quality results for 'Waitohi' included enhanced sprout resistance, with the mean falling number value about 20 to 70 s higher than 'CRDW17'. The combination of increased protein content and less sprout damage may be the explanation for the preferred flour rheological properties of 'Waitohi' compared with 'CRDW17'.

'Waitohi' had increased grain yellowness. However, enhanced grain yellowness did not relate to flour or pasta colour and thus was not advantageous to millers or processors. In fact, the opposite was true with lower b* values for 'Waitohi' flour and pasta. This significant cultivar effect showed 'CRDW17' had yellower flour and pasta b* values at all sites and across all N treatments. In addition to lower b* values, 'Waitohi' had higher corresponding flour a* values than 'CRDW17'. This may be an indication that there is a relationship between a* and b* values. It could be that instead of increasing b* values a decrease in a* value is required to achieve the preferred colour. This supports results from Penno (1996) who reported a negative relationship between the colour of preference and the redness of the sample in oat groat colour. It could be that use of solely b* values is not an appropriate measure for colour preference in the pasta industry, but at this stage it is a useful screening test. In future, the red colour of a sample may also need to be evaluated.

The higher flour b* was due to the higher carotenoid concentration in the flour for 'CRDW17' compared with 'Waitohi'. The implication of these results was that the preferred yellow colour for flour and hence pasta production can be obtained by cultivar selection, namely using 'CRDW17'.

Despite the positive colour attributes of 'CRDW17', the increased sprout susceptibility and lower protein grain values compared with 'Waitohi', may discourage growers from selecting 'CRDW17' if they were not paid a higher premium to grow it. Consideration should be given, by industry, to the other attributes of 'CRDW17' besides colour. Caution should be taken if industry decides to promote the use of only 'CRDW17'. If the entire durum growing area was sown in 'CRDW17' the risk of loss of product through sprout damage would be increased. The use of 'Waitohi' could be thought of as an 'insurance policy' due to it being less likely to sprout in a wet growing season in comparison with 'CRDW17'. Similarly, the erratic nature of late season rainfall in Canterbury could result in complete crop failure in one area. It seems prudent to continue to have durum wheat grown in several distinct regions in Canterbury to decrease the risk of crop failure. The combination of yield, grain, flour and pasta quality results from this study indicates that a compromise may be required in cultivar selection, if processors are to meet the consumer demands for pasta of golden colour. 'CRDW17' consistently had higher flour and pasta yellowness. However, the negative agronomic attributes of may discourage growers from selecting 'CRDW17' if they were not paid a higher premium to grow it.

Finally, for the industry to progress the onus must be on breeders to develop a cultivar that has the positive agronomic traits found in 'Waitohi' coupled with the positive colour attributes of 'CRDW17'. Essentially, this project has determined that greater colour improvement is likely to come from plant breeding than can be achieved agronomically through N management. Of relief was the result that current N management practices do not adversely affect flour or pasta colour.

6.1 Future research

Further research into establishing why different wheat cultivars have different colour properties, for example to determine if it an increase in carotenoid synthesis or a difference in the partitioning of pigments in the grain would be beneficial to the pasta industry. Also, the effect of different extraction rates on the colour of the resulting flour also needs to be investigated.

In addition, the use of a* values in measuring preferred pasta colour needs to be investigated further. There may be a link between most preferred pasta and flour colour and a move away from the red region of the colour chart which would imply that the a* measurement may be a more accurate measure than the b* component.

6.2 Conclusions

- Growers can produce high yielding crops of preferred quality durum wheat by using N management and cultivar selection.
- Current N management used to increase yield, application of N at tillering, produced crops of required protein content and also generated variability in four and pasta yellowness, with early N having a tendency to enhance flour yellowness.
- 'Waitohi' had more favourable agronomic traits than 'CRDW17', including higher protein content, falling number value and more preferred rheological properties.
- Durum breeding must focus on positive agronomic traits of 'Waitohi' coupled with 'CRDW17' as it could not be achieved by agronomic treatments.

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References

American Association of Cereal Chemists, Inc. (1983). Approved Methods of the American Association of Cereal Chemists (8th ed.). St Paul, Minnesota: American Association of Cereal Chemists, Inc.

American Association of Cereal Chemists, Inc. (1995). Approved Methods of the American Association of Cereal Chemists (9th ed.). St Paul, Minnesota: American Association of Cereal Chemists, Inc.

Austin, R.B., Bingham, J., Blackwell, R.D., Evans, L.T., Ford, M.A., Morgan, C.L. and Taylor, M. (1980). Genetic improvements in winter wheat yields since 1900 and associated physiological changes. *Journal of Agricultural Science, Cambridge*, **94**, 675-689.

Blacklow, W.M. and Incoll, L.D. (1981). Nitrogen stress of winter wheat changed the determinants of yield and the distribution of nitrogen and total dry matter during grain filling. *Australian Journal of Plant Physiology,* **8**, 191-200.

Boggini, G. (1985). Bread making quality of some durum wheat cultivars. *Technical Molitori,* 36, 579-583. Cited by: Boyacioglu, M.H. and D'Appolonia, B.L. in *Cereal Chemistry* 1994 **71**, 21-28.

Borrelli, G.M., Troccoli, A., Di Fonzo, N. and Fares, C. (1999). Durum wheat lipoxygenase activity and other quality parameters that affect pasta colour. *Cereal Chemistry,* **76**, 335-340.

Boyacioglu, M.H. and D'Appolonia, B.L. (1994). Characterisation and utilisation of durum wheat for breadmaking. I. Comparison of chemical, rheological, and baking properties between bread wheat flours and durum wheat flours. *Cereal Chemistry*, **71**, 21-28.

Bozzini, A., Fabriani, G. and Lintas, C. (1988). Origin, distribution and production of durum wheat in the world. *In*: G. Fabriani (ed.). Durum Wheat: Chemistry and Technology. St Paul, Minnesota: American Association of Cereal Chemists, Inc.; 1-16.

Brocklehurst, P.A. (1977). Factors controlling grain weight in wheat. *Nature*, **266**, 348-349.

Cameron, K.C. (1992). Nitrogen in soil. *In*: W.A. Nierenberg (ed.). Encyclopedia of Earth System Science. New York: Academic Press; (**3**) 307-317.

Clarke, J.M., Marchylo, B.A., Kovacs, M.I.P., Noll, J.S., McCaig, T.N. and Howes, N.K. (1998). Breeding durum wheat for pasta quality in Canada. *In*: H.J. Braun, F. Altay, W.E. Kronstad, S.P.S. Beniwal and A. McNab (eds.). Wheat: prospects for global improvements. Boston: Kluwer Academic Publishers; 229-236.

Cromey, M.G. and Mulholland, R.I. (1988). Blackpoint of wheat: fungal associations, cultivar susceptibility and effects on grain weight and germination. *New Zealand Journal of Agricultural Research*, **31**, 51-56.

Cox, J.E. (1978). Soil and agriculture, part of Paparua County, Canterbury, New Zealand. *New Zealand Soil Bureau Bulletin*, **34**.

Damidaux, R., Autran, J.C., Grignac, P. and Feillet, P. (1978). Mise en evidence de relations applicables en selection entre l'electrophoregramme des gliadines et les proprietes visoelastiques du gluten de *Triticum durum* Desf C.R Hedb. sceances Academie. Science: Paris. **291**, 585-588. Cited by: Feillet, P. in Durum Chemistry and Technology 1988, 93-109.

Dell'Aquila, A., Colaprico, G., Taranto, G., Carella, G. (1983). Endosperm changes in developing and germinating *T. aestivum, T. turgidum* and *T. monococcum* seeds. *Cereal Research Communications*, **11**, 107-113. Cited by: Stone, P.J. and Savin, R. in Wheat, Ecology and Physiology of Yield Determination 1999, 85-120.

Dexter, J.E. and Matsuo, R.R. (1977). Influence of protein content on some durum wheat quality parameters. *Canadian Journal of Plant Science*, **57**, 717-727.

Dexter, J.E. and Matsuo, R.R. (1980). Relationship between durum wheat protein properties and pasta dough rheology and spaghetti cooking quality. *Journal of Agricultural Food Chemistry*, **28**, 896-899. Cited by: Boyacioglu, M.H. and D'Appolonia, B.L. in *Cereal Chemistry* 1994, **71**, 21-28.

Dexter, J.E., Matsuo, R.R. and Kruger, J.E. (1990). The spaghetti-making quality of commercial durum wheat samples of variable α-amylase activity. *Cereal Chemistry,* **67**, 405-412.

Dexter, J.E., Marchylo, B.A., Clear, R.M. and Clarke, J.M. (1997). Effect of fusarium head blight on semolina milling and pasta-making quality of durum wheat. *Cereal Chemistry*, **74**, 519-525.

Dougherty, C.T., Scott, W.R. and Langer, R.H.M. (1975). Effects of sowing rate, irrigation and nitrogen on the components of yield of spring-sown semidwarf and standard New Zealand wheats. *New Zealand Journal of Agricultural Research*, **18**, 197-207.

Drewitt, E.G. and Dyson, C.B. (1987). Grain yield and quality responses to early and late applications of nitrogen in three spring wheat cultivars under three irrigation levels. *Proceedings of the Agronomy Society of New Zealand*, **17**, 71-78.

Drewitt, E.G. and Smart, J.G. (1981). The effect of irrigation and nitrogen fertiliser on the yield and malting quality of barley. *Agronomy Society of New Zealand,* **11**, 23-28.

Ellen, J. and Spiertz, J.H.J. (1978). Effects of nitrogen on crop development and grain growth of winter wheat in relation to assimilation and utilisation of assimilates and nutrients. *Netherlands Journal of Agricultural Sciences*, **26**, 210-231.

Evans, L.T. (1993). Crop Evolution, Adaptation and Yield. Cambridge, U.K: Cambridge University Press. Cited by: Stone, P.J. and Savin, R. in Wheat, Ecology and Physiology of Yield Determination 1999, 85-120.

Fabriani, G. and Lintas, C. (1988). Durum Chemistry and Technology. St Paul, Minnesota: American Association of Cereal Chemists, Inc.;1-332

Feillet, P. (1988). Protein and enzyme composition of durum wheat. *In*: Fabriani, G. and Lintas, C. (eds.). Durum Chemistry and Technology. St Paul, Minnesota: American Association of Cereal Chemists Inc.; 93-109.

Feillet, P. and Bourdet, A. (1964). Sur le comportement electrophoretique en gel d'amidon des proteines du ble solubles en milieu salin neutre. C.R Hedd. Seances Academie du Science. 258-292. Cited by: Feillet, P. in Durum Chemistry and Technology 1988, 93-109.

Fergusson, A.G. (1999). Grain yield and quality of malting barley (*Hordeum vulgare*.L) as influenced by nitrogen. Unpublished Masters thesis, Lincoln University, Lincoln, New Zealand.

Gallagher, J.N., Biscoe, P.V. and Scott, R.K. (1975). Barley and its environment. V. Stability of grain weight. *Journal of Applied Ecology*, **12**, 319-336.

Gonnet, J.F. (1995). A colorimetric look at the RHS chart - Perspectives for an instrumental determination of colour codes. *Journal of Horticultural Science*, **70**, 191-206.

Graham, J.S.D. and Morton, R.K. (1963). Studies of proteins of developing wheat endosperm: separation by starch-gel electrophoresis and incorporation of [35 S] sulphate. *Australian Journal of Biological Sciences*, **16**, 357-365.

Grindlay, D.J.C. (1997). Towards and explanation of crop nitrogen demand based on the optimization of leaf nitrogen per unit leaf area. *Journal of Agricultural Science, Cambridge*, **128**, 377-396.

Gupta, R.B., Khan, K. and MacRitchie, F. (1993). Biochemical basis of flour properties in bread wheats. I. Effects of variation in the quantity and size distribution of polymeric protein. *Journal of Cereal Science*, **18**, 23-41.

Gupta, R.B., Paul, J.G., Cornish, G.B., Palmer, G.A., Bekes, F. and Rathjen, A.J. (1994). Allelic variation at glutenin subunit and gliadin loci, Glu-1, Glu-3 and Gli-1 of common wheats. I. Its additive and interactive effects on dough properties. *Journal of Cereal Science*, **19**, 9-17.

Hay, R.K. and Walker, A.J. (1989). An introduction to the physiology of crop yield. Harlow, England: Longman; 292pp.

Hampton, J.G., McCloy, B.L. and McMillian, D.R. (1981). Ear populations and wheat production. *New Zealand Journal of Experimental Agriculture*, **9**(2), 185-189.

Hunt, L.A., van der Poorten, G. and Pararajasingham, S. (1991). Postanthesis temperature effects on duration and rate of grain filling in some winter and spring wheats. *Canadian Journal of Plant Science*, **71**, 609-617.

International Wheat Council. (1982). The world durum wheat situation. Secretariat Paper12. The Council, London. Cited by: Fabriani, G. and Lintas, C. in Durum Chemistry and Technology 1988; 7pp.

Irvine, G.N. (1959). Effect of temperature on the kinetics of the lipoxidase system of wheat. *Cereal Chemistry*, **26**, 507-511.

Irvine, G.N. (1971). Durum wheat and pasta products. *In*: Y. Pomeranz (ed.). Wheat Chemistry and Technology, (2nd ed.). St Paul, Minnesota: American Association of Cereal Chemistry; 777-796.

Irvine, G.N. and Anderson, J.A. (1953). Variation in principal quality factors of durum wheat with a quality prediction test for wheat or semolina. *Cereal Chemistry*, **30**, 334-342.

Irvine, G.N. and Winkler, C.A. (1950). Factors affecting the colour of macaroni. II: Kinetic studies of pigment destruction during making. *Cereal Chemistry*, **27**, 205-218.

Jamieson, P.D. and Wilson, D.R. (1992). Physiological and agronomic limits to wheat yield and quality. *In*: Wheat symposium: Limits to production and quality. *Agronomy Society of New Zealand.* Special publication No. **8**. Lincoln University, 2nd July. 25-32.

Jenner, C.F., Ugalde, T.D. and Aspinall, D. (1991). The physiology of starch and protein deposition in the endosperm of wheat. *Australian Journal of Plant Physiology*, **18**, 211-226.

Jennings, A.C. and Morton, R.K. (1963). Amino acids and protein synthesis in developing wheat endosperm. *Australian Journal of Biological Sciences*, **16**, 384-394.

Johnson, N.J., Moot, D.J. and Lindley, T.N. (1997). Oat groat colour-a quality factor. *Proceedings of the Agronomy Society of New Zealand*, **27**, 79-82.

Keeney, R.P. and Bremner, J.M. (1967). Comparison and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal*, **58**, 493-503.

van Keulen, H. and Seligman, N.G. (1987). Simulation of water use, nitrogen nutrition and crop growth of a spring wheat crop. Wageningen, Netherlands: Pudoc Wageningen; 310pp.

Langer, R.H.M. (1965). A study of New Zealand wheats. I. Growth and yield characteristics. *New Zealand Journal of Agricultural Research*, **8**, 10-14.

Langer, R.H.M. (1979). The dynamics of wheat yield. *New Zealand Wheat Review*, **14**, 32-40.

Langer, R.H.M. and Liew, F.K.Y. (1973). Effects of varying nitrogen supply at different stages of the reproductive phase on spikelet and grain production and on grain nitrogen wheat. *Australian Journal of Agricultural Research*, **24**, 647-656.

Laignelet, B. (1983). Lipid in durum wheat and pasta products. *In:* P.J Barnes (ed.). Lipids in Cereal Technology. London: Academic Press; 269-286.

Leloup, V.M., Colonna, P. and Buleon, A. (1991). Influence of amylose-amylopectin ratio on gel properties. *Journal of Cereal Science*, **13**, 1-13.

Lepage, M. and Sims, R.P.A. (1968). Carotenoids of wheat flour: their identification and composition. *Cereal Chemistry*, **45**, 600-604.

Little, A.C. (1975). A research note: off on a tangent. *Journal of Food Science*, **40**, 410-411.

Luraschi, A. (1955). Trattato della Moderna Panificazione. Hoepli, Milan. Cited by: Fabriani, G. and Lintas, C. in Durum Chemistry and Technology 1988, 266.

McGee, H. (1991). On food and cooking. *In*: The Science and Lore of the Kitchen. London: Harper Collins. Cited by: Stone, P.J. and Savin, R. in Wheat, Ecology and Physiology of Yield Determination 1999, 85-120.

McLaren, R.G. and Cameron, K.C. (1996). Soil Science: Sustainable production and environmental protection (2nd ed.). Auckland: Oxford University Press; 304 pp.

Markley, M.C. and Bailey, C.H. (1935). The nature of the pigments of the gasoline extract of wheat. *Cereal Chemistry*, **12**, 33-39.

Martin, R.J. (1987). The effect of time and nitrogen application on the yield and quality of contrasting cultivars of autumn sown wheat. *Proceedings of Agronomy Society of New Zealand*, **17**, 103-108.

Martin, R.J., Saville, D.J., Daly, M.J. and Drewitt, E.G. (1989). The effects of nitrogen fertiliser on the relationship between yield and quality in wheat and barley. *Proceedings of the Workshop on Nitrogen in New Zealand Agriculture and Horticulture,* Massey University, Palmerston North. Fertiliser and Lime Research Occasional Report No. **3**, 346-358.

Martin, R.J., Sutton, K.H., Moyle, T.N., Hay, R.L. and Gillespie, R.N. (1992). Effect of nitrogen fertiliser on the yield and quality of six cultivars of autumn-sown wheat. *New Zealand Journal of Crop and Horticultural Science*, **20**, 273-282.

Matsuo, R.R. (1994). Durum wheat: its unique pasta-making properties. *In*: W. Bushuk and V.F. Rasper (eds.). Wheat Production, Properties and Quality (1st ed.). Glasgow: Blackie Academic and Professional; 169-177.

Matsuo, R.R., Bradley, J.W. and Irvine, G.N. (1970). Studies on pigment destruction during spaghetti processing. *Cereal Chemistry*, **47**, 1-5.

Matsuo, R.R., Dexter, J.E. and MacGregor, A.W. (1982). Effect of sprout damage on durum wheat and spaghetti quality. *Cereal Chemistry*, **59**, 468-472.

Matsuo, R.R. and Irvine, G.N. (1970). Effect of gluten on the cooking quality of spaghetti. *Cereal Chemistry*, **47**, 173-176.

Matsuo, R.R., Bradley, J.W. and Irvine, G.N. (1972). Effect of protein content on the cooking quality of spaghetti. *Cereal Chemistry*, **49**, 707-711.

Mattern, P.J., Morris, R., Schmidt, J.W. and Johnson, V.A. (1973). Location of genes for kernel properties in the wheat variety 'Cheyenne' using chromosome substitution lines. *In*: Proceedings of the 4th International Wheat Genetics Symposium, Columbia, Missouri, USA, 703-707.

MetService. (1983). *New Zealand Climate Regions.* Wellington: New Zealand Meteorological Service; Map 1.

Minitab. (1989). Minitab reference manual: Release 7. Valley Forage, Pennsylvania: Data Technology Industries, Inc.

Moot, D.J. and Every, D. (1990). A comparison of bread baking, falling number, α-amylase assay and visual method for the assessment of pre-harvest sprouting in wheat. *Journal of Cereal Science*, **11**, 225-234.

Moot, D.J., Henderson, A.L., Porter, J.R. and Semenov, M.A. (1996). Temperature, CO_2 and the growth and development of wheat: changes in the mean and variability of growing conditions. *Climatic Change*, **33**, 351-368.

Morgenstern, M. (1992). Tristimulus colour measurement of flour. Christchurch: DSIR, DSIR Crop Research Food Report No. 10.

Morris, C.F. and Rose, S.P. (1996). Wheat. *In*: Henry, R.J. and Kettlewell, R.S. (eds.). Cereal Grain Quality. London: Chapman & Hall; 3-54.

Osborne, T.B. (1907). The proteins of the wheat kernel. Publications of the Carnegie Institution Washington, vol. **84**. Washington: Judd and Detweiler. Cited by: Stone, P.J. and Savin, R. in Wheat, Ecology and Physiology of Yield Determination 1999, 85-120.

Pence, J.W., Weinstein, N.E. and Mecham, D.K. (1954). Differences in the distribution of components in albumin preparations from durum and common wheat flour. *Cereal Chemistry*, **31**, 396-400.

Penno, N.J. (1996). Colour of oat groats: a quality factor. Honours dissertation, Lincoln University, Lincoln, New Zealand.

Pomeranz, Y. (ed.). (1971). Wheat Chemistry and Technology (2nd ed.). St Paul, Minnesota: American Association of Cereal Chemists, Inc.; 799 pp.

Power, J.F. and Alessi, J. (1978). Tiller development and yield of standard and semi-dwarf spring varieties as affected by nitrogen fertiliser. *Journal of Agricultural Science, Cambridge*, **90**, 97-108.

Quaglia, G.B. (1988). Durum wheat bread colour. *In*: G. Fabriani and C. Lintas (eds.). Durum Chemistry and Technology. St Paul, Minnesota: American Association of Cereal Chemists, Inc.; 263-281.

Schofield, J.D. (1994). Wheat proteins: Structure and functionality in milling and breadmaking. *In*: W. Bushuk and V.F. Rasper (eds.). Wheat: Production, Properties and Quality (1st ed.). Glasgow: Blackie Academic and Professional; 73-99.

Scott, W.R., Martin, R.J. and Stevenson, K.R. (1992). Soil fertility limitations to wheat yield and quality. *In*: Wheat Symposium: Limits to production and quality. *Agronomy Society of New Zealand*, Special publication No. 8. Lincoln University, 2nd July. 47-56.

Silano, V., Decillis, U., De ponte, R., D'Errico, A.M. and Pocchiari, F. (1968). L/analisi delle composizioni ellettroforetiche di estratti protein albuminici e glubulinici nella differenziazione del *Triticum aestivum* dal *Triticum durum*. Ric scientific, **38**, 745. Cited by Feillet, P. in Durum Chemistry and Technology 1988, 93-109.

Slafer, G.A., Araus, J.L. and Richards, R.A. (1999). Physiological traits that increase the yield potential of wheat. *In*: E.H. Satorre and G.A. Slafer (eds.). Wheat, Ecology and Physiology of Yield Determination. New York: Food Products Press; 379-415.

Soulaka, A.B. and Morrison, W.R. (1985). The amylose and lipid contents, dimensions and gelatinisation characteristics of some wheat starches and their A-and B- granule fractions. *Journal of the Science of Food and Agriculture*, **36**, 709-718.

Stephen, R.C., Saville, D.J. and Drewitt, E.G. (1997). Relationship between wheat grain yield and plant available soil N and monthly rainfall and potential evapotranspiration. *Proceedings of the Agronomy Society of New Zealand*, **27**, 145-150.

Stephen, R.C., Saville, D.J. and Kemp, T.N. (1985). Responses of grain yield components of winter sown wheat to nitrogen fertiliser applied at four growth stages. *Proceedings Agronomy Society of New Zealand*, **15**, 59-63.

Stone P.J. and Savin, R. (1999). Grain quality and its physiological determinants. *In*: E. Satorre and G. Slafer (eds.). Wheat, Ecology and Physiology of Yield Determination. New York: Food Products Press; 85-120.

Stone, P.J. and Nicolas, M.E. (1996). Varietal differences in mature protein composition of wheat resulted from different rates of polymer accumulation during grain filling. *Australian Journal of Plant Physiology*, **23**, 727-737.

Thorne, G.N. and Wood, D.W. (1988). Contributions of shoot categories to growth and yield of winter wheat. *Journal of Agricultural Science, Cambridge*, **111**, 290-294.

Tipples, K.H., Kilborn, R.H. and Preston, K.R. (1994). Bread – wheat quality defined. *In*: W. Bushuk and V.F. Rasper (eds.). Wheat Production, Properties and Quality (1st ed.). Glasgow: Blackie Academic and Professional; 25-36.

Walsh, D.E. and Giles, K.A. (1971). The influence of protein composition on spaghetti quality. *Cereal Chemistry*, **48**, 544-548.

Wrigley, C.W., Autran, J.C. and Bushruk, W. (1982). Identification of cereal varieties by gel electrophoresis of the grain proteins. *Advances in Cereal Science and Technology*, **5**, 211-214.

Zadoks, J.C., Chang, T.T. and Konzak, C.F. (1974). A decimal code for the growth stages of cereals. *Weed Research*, **14**, 415-421.

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Appendix

Appendix 1. Mean water absorption, stability and development time values for two durum wheat cultivars ('CRDW17' and 'Waitohi') grown at Wakanui with different late N applications (0, 50 and 100 kg N/ha) and with either 150 kg N/ha applied at tillering or not at all.

Wakanui

Cultivar	Early N (kg/ha)	Late N (kg/ha)	Water absorption (%)	Stability time (minutes)	Develop. time (minutes)
'CRDW17'	0	0	67.2	1.5	2.0
	0	50	68.5	1.4	1.9
	0	100	69.2	1.7	2.2
	150	0	68.8	1.9	2.2
	150	50	68.5	1.9	2.4
	150	100	66.6	2.5	2.3
Mean	-	-	68.1	1.8	2.2
'Waitohi'	0	0	68.5	2.4	2.5
	0	50	69.4	2.5	2.5
	0	100	70.4	2.7	2.8
	150	0	70.4	2.2	2.4
	150	50	69.5	1.9	2.6
	150	100	70.1	1.8	2.6
Mean	-	-	69.7	2.3	2.6
SEmax	-	-	0.90	0.20	0.17
Significance * = 0.05 ** = 0.01 *** = 0.001			CV*	CV** CV * Early N***	CV**